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Study on Relationship of Moisture content and Shear Strength in chemically treated Bambusa nutans culms available in Nepalese market

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Abstract
The paper explores the longstanding usage of *Bambusa nutans*, or Maal Bans, as a prominent bamboo species in Nepalese construction. Bamboo that has been treated with borax-boric acid solution that was recently shipped into the lab, served as the experiment's sample population. This study investigates the correlation between moisture content/ mechanical properties and shear strength in these bamboo samples. Utilizing characteristic values obtained from laboratory tests following ISO 12122-1 standards, adjustments based on specific variables can be made to derive design values. Emphasis is placed on utilizing the fifth percentile value of the sample population with a 75% confidence for determining design values, a crucial aspect addressed in this study. This characteristic value for shear strengths calculated from three different data-sets is also referred.

Keywords
shear strength parallel to fiber, influence of moisture content, Nepalese bamboo, determination of characteristic value, bamboo structures

1. Introduction

Bamboo is a more-practical building material that is inexpensive, quick to grow, and aesthetically pleasing. In seismically active areas like Nepal, it's excellent strength to weight ratio makes it an even better structural material. Due to the shear forces acting on their ends, round bamboo culms—which are most likely to be used as axial members—are prone to splitting. Shear parallel to fiber typically has the lowest numerical strength value among the other bamboo strength parameters.

Except in Antarctica and Europe, bamboo as giant grass is native to all other continents [1] . Among 1250 worldwide species of bamboo less than 100 have shown the potential to be used as structural material [2]. Place where bamboos are native, bamboo has also been a part of culture, whether it be as food, as goods for rites, or as a part of architecture. From the beginning of civilization, Bamboos are being used for construction and are still extensively used vernacularly to present day Nepal. In China, extensive use has been documented throughout history. Bamboo have long been associated in religious and cultural rituals, particularly in East and Southeast Asia. Compared to the history of its use, the study of bamboo is newly introduced. Some of the recorded works like by Azuola-Guerra (1887), Meyer and Ekelund (1923) are oldest among studies related to bamboo [2].

Different national and international standards have been published and are in use, recognizing bamboo as building material. Countries like USA, Ecuador, Colombia, Peru, India and China have their own national standards relating to harvesting, grading, selecting and using structural bamboo. ISO standards related to bamboo have largely been adopted over world and have standards for structural design (ISO 22156:2021), Physical Grading [3], and test method for physical/ mechanical properties determination [4]. As a natural material, there are many variables that might alter strengths of bamboo. Because of this, using bamboo in a rational way can be difficult because the material's qualities vary widely from place to place and over time. [5] has shown bamboo is a more sustainable material than steel, concrete or timber and house constructions, are also cheaper and are more sustainable than reinforced masonry counterparts [6]. With advantages like inexpensiveness, strength, sustainability, acoustic and aesthetic property it is often called as 'poor-man's timber' but people are reluctant about its use in general. To break this stigma, research focusing on local species of bamboo can do evidence-based defense to use particular bamboo in that region.

1.1 Bamboo reinforced concrete

Discussions like using bamboo substitute for other conventional material in composite material (like steel reinforcement in concrete) also arise. [7] on this topic proposes that using bamboo and concrete is not as suitable as it is perceived to be, as bond between bamboo and concrete is very weak and tackling this problem will also result in bulkier sections or expensive and toxic treatments. For further discussion on using bamboo in structures, we have an alternative of using round bamboo which seems like easier and faster construction technology.

For rational design of round bamboo structures, the first step is to characterize its mechanical properties and also its physical irregularities of specific type of bamboo. Mechanical property characterization would help to use values of material strengths with confidence while characterized physical irregularities would give the idea of usability of bamboo in particular space of the structure. Different bamboo characterization literature suggests that the shear is the most critical property in using round bamboo.

1.2 Peculiarity in Nepal

Nepal lies in the belt of the Himalayas, one of the youngest mountain ranges in world, and thus the climate here in the basin is also very much unique, topography is rough, and these parameters could possibly change the morphology and other characteristics in fauna and flora. In tropical country, bamboo seems to occupy large area of the forest, example 5% of reserve forest (natural habitat) in Malaysia is covered with bamboo [8], signifying that bamboo thrives in that tropical climate and there might be more favorable material properties of same species of bamboo than in other climatic conditions. But in Nepalese climatic condition that may not be same, thus for specific region, a species should be characterized uniquely and so does other effects should be studied.

2. Materials and Methods

Materials: Bambusa nutans culms are procured from one of the treated-bamboo-supplier, this way sampling was random among the market grade bamboo culms. As per supplier, these bamboo are harvested and treated in Jhapa district and later transported to Lab in Kathmandu valley. The treatment bores were drilled near the nodes at an angle such that one drill axis bores two holes in opposite face of the culms piercing the diaphragm in the one go. The culms are of minimum of 6m length and maximum upto 6400mm. Average Moisture content of samples after procurement is 38.3% and one sample got moisture as high as 54.9%. Shear plates (Bow-tie apparatus) is fabricated. Twenty samples are taken from different culms from these culms then tested.

Grading: Grading process of the supplied poles is conducted following ISO 19624:2018 before cutting. Initially these culms are graded visually for any defects then geometrical dimensions are measured with instruments with different precision. Several measurements on single culms are done so that there is sufficient data to characterize culm's irregularities in terms of bow, taper and ovality. These are done only for future reference and are not directly related with the scope of this paper.

Nomenclature of the test specimen Nomenclatures of specimens are done so that each specimen are uniquely represented with its species, culm's serial number and test name (Eg. Bn_SH_105X_IN represents Bambusa nutan's shear specimen from internode of 105th culm, X is optional character representing extra specimen from the same culm after Bn_SH_105_IN specimen showed any flaw during the test, note: here the culms are named starting from 101)

Preparation of test specimens: As per ISO 22157:2019, Shear tests parallel to fiber shall be made on specimens, 50% with a node and 50% without, but this measure is not followed for the experiments, which is because majority of the culm's nodal region is damaged with cracks. The cracks may be caused due to (relatively) rapid evaporation through treatment-boreholes. According to the ISO standards, length should be taken as the lesser of the outer diameter, D or 10 times the wall thickness (δ) and if D is 20mm or less, the height may be taken as twice the outer diameter, 2D, irrespective of δ. All the length of the specimens is taken to the standards.

Then measurement of the every dimension of cut sample is done with a Vernier caliper with precision 10^{-2}mm. Heights are measured in three random points. The formula provided by ISO 22157 is applied to determine the shear strength of each specimen. The formula is modified to use the specimen's average length as follows:

$$\mathrm{f_v} = \frac{F_{\max}}{4 \times \mathrm{Avg(L)} \times \mathrm{t}} \tag{1}$$

F_{max} = maximum load, in Newtons, at which the specimen fails
Avg(L) = Average height of the specimen measured in 3 random direction
$\Sigma\delta$= sum of the measured wall thickness
f_v = Lower bound strength

Apparatus: Tests are carried out in AIMIL UTM, with load precision 10^{-2} N and displacement precision 10^{-6}mm. The test setup is equipped with semi-spherical bearing, loading plate, bow-tie apparatus, and made sure that load is concentrically applied. All testing equipment in the UTM is calibrated by Nepal Standard.

Shear Plates: Two number of bow tie apparatus (shear plates) is prepared for testing the prepared specimens. The specimen is supported at its lower end over two opposing quadrants, and loaded at its upper end over the two opposing quadrants. Hence, loading the specimen in this way, resulted in four shear areas as shown in figure 1.

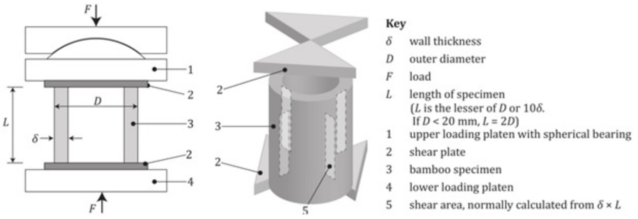

Figure 1: shear test setup and shear planes with bow-tie apparatus (ISO 22157:2019) ([4])

Testing of specimen and Load application: Test specimens with required setup is placed and made aligned with loading axis and center of shear plates, specimen, and loading is also aligned. Small load of not more than 1% of expected failure load was initially applied to seat the specimen (ISO 22157:2019). Displacement controlled loading is applied continuously in the setup at such a rate that failure occurs in about 5 min.

Figure 2: lab setup for shear test

Data extraction and Analysis: Digital data are extracted and then visualized and interpreted using Python and MS Excel.

Some of the principle formula recommended for calculating characteristic value, as per ISO 12122-1, are listed as below:

$$X_{\text{mean, 0.75}} = X_{\text{mean}} \left(1 - \frac{k_{\text{mean, 0.75}}\, V}{\sqrt{n}}\right) \tag{2}$$

Where,
$X_{(\text{mean},0.75)}$ is the characteristic value expressed as the mean value with 75% confidence
X_{mean} is the average of the individual test values (X_i)
$k_{(\text{mean},0.75)}$ is a multiplier to give a mean value with 75% confidence and shall be the value obtained
V is the coefficient of variation of the test data found by dividing the standard deviation of the test data by the average of the test data

$$X_{\text{mean, 0.75}} = X_{\text{mean}} \left(1 - \frac{0.728441\, V}{\sqrt{20}}\right) \tag{3}$$

A.2.2 Use of non-parametric data analyzed using AS/NZS 4063.2

$$X_{0.05,0.75} = X_{0.05} \left(1 - \frac{k_{0.05,0.75}\, V}{\sqrt{n}}\right) \tag{4}$$

Where,
n is the number of test values
$X_{0.05,0.75}$ is the 5 percent lower tolerance limit with 75% confidence
$X_{0.05}$ is the 5^{th} percentile from the test data
$k_{0.05,0.75}$ is a multiplier to give the 5 percent lower tolerance limit with 75% confidence
V is the coefficient of variation of the test data found by dividing the standard deviation of the test data by the average of the test data

Characteristic Values For determination of characteristic values of shear strengths in three of the datasets, namely: samples with relatively normal moisture content (NMC), relatively higher moisture content (HMC) and both of them combined; ISO 12122-1 is followed and number of samples taken for analysis are 30, 20 and 50 respectively.

Densities As prescribed by ISO 22157:2019 three types of densities are calculated Volume measurement by immersion is not possible for maintaining same moisture content hence, authors hypothesized the volume immediately after the test is equal to the volume just before the test, i.e, V = Vo.

$$\rho = \frac{m_o}{V_o} \tag{5}$$

$$\rho_{12} = \rho_{\text{test}} * \frac{1.12}{1+w} \tag{6}$$

$$\rho_{\text{test}} = \frac{m_e}{V} \tag{7}$$

Where,
ρ = basic density
ρ_{12}= density at 12% moisture content
ρ_{test}= density at time of test
m_o = oven dry mass of the test specimen in gm
m_e = mass of the test piece in grams
V = volume of the test piece in mm3
V_o = volume of the green test piece in mm^3
w = moisture content in decimal

3. Results

Nearly all of the specimen had brittle nature of failure with two cracks in two directions as shown in figure (a). Comparatively thicker specimens appeared to be cracked without clean splits as shown in figure (b). Thin walled specimens had more simultaneous rupture in all directions (c). For nodal specimen cracks propagates into the diaphragm to meet at a point in the diaphragm (d).

Figure 3: typical failure patterns

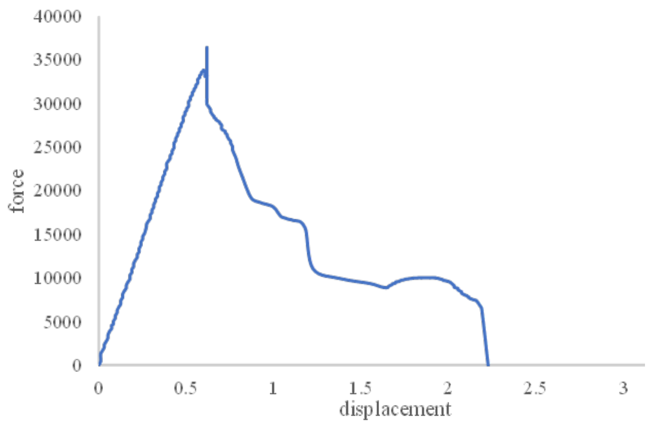

Figure 4: typical force-displacement curve for shear test of bamboo (after initiation of first failure point, rest of the curve is quite unpredictable)

Table 1: Statistics for overall dimensions, moisture content, and shear strength

Parameters ⇓	**Average**	**Standard Deviation**
Average length	66.65	6.27
Average overall thickness	10.5	4.11
Average overall diameter	67.42	5.33
Moisture content	33.22	10.92
Shear strength	8.5	3.17

Upon analysis for characteristic value of Shear strength for different datasets, namely: ’Normal moisture content’, ’High moisture content’ & both of them combined; table 2 illustrates the values obtained.

The ’shape’ and ’scale’ for log-normal cdf equation for these three datasets are as follows:

a) NMC: shape = 0.287757, scale = 8.11027

b) HMC: shape = 0.348730, scale = 7.98620

c) Combined: shape = 0.313663, scale = 8.06041

Table 2: Statistics from analysis for characterized value of three different datasets

Data Set for Shear Strength ⇒	**NMC**	**HMC**	**Combined**
Data Points	30	20	50
Mean	8.413	8.4957	8.446
S.D.	2.0718	3.0907	2.5295
Coeff. Of Variation	0.2462	0.36%	0.30%
5th percentile	5.0979	4.9896	4.9075
95th percentile	11.4006	14.6122	12.1227
Mean of logarithm	2.0931	2.0777	2.0869
KS-test statistic	0.1587	0.10344	0.10842
KS-test p-value	0.3949	0.9679	0.5622
5th percentile ch. Value with 75% confidence	4.83	4.49	4.67
95th percentile ch. Value with 75% confidence	12.01	16.07	12.7

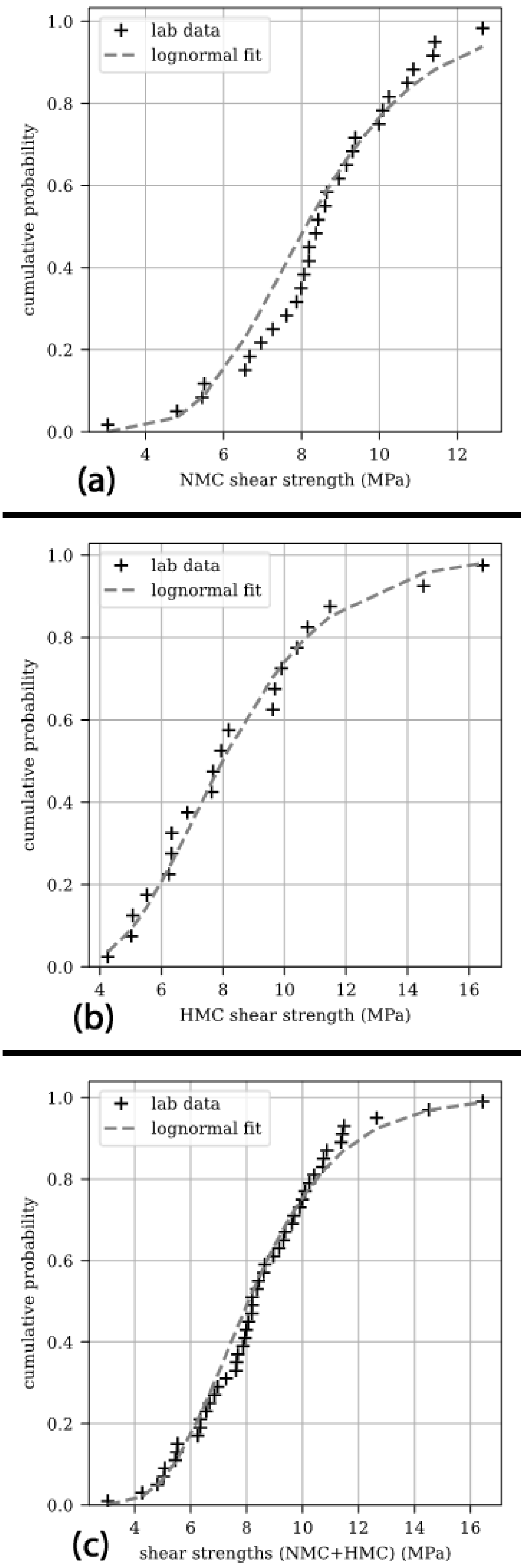

Figure 5: fitting log-normal distribution to shear strengths of different datasets

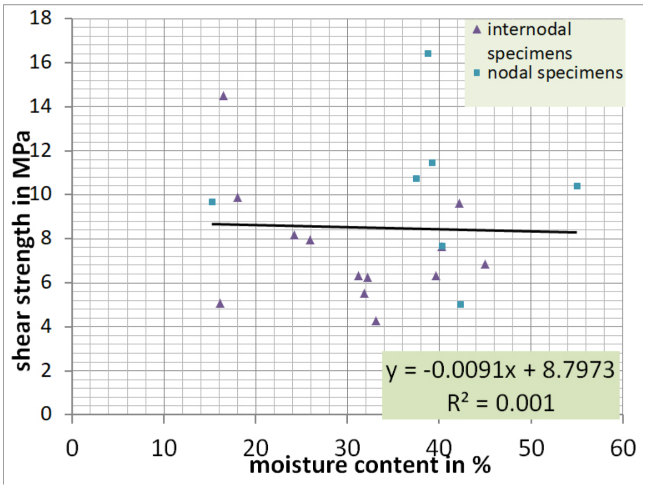

Figure 6: relation between moisture content and shear strength

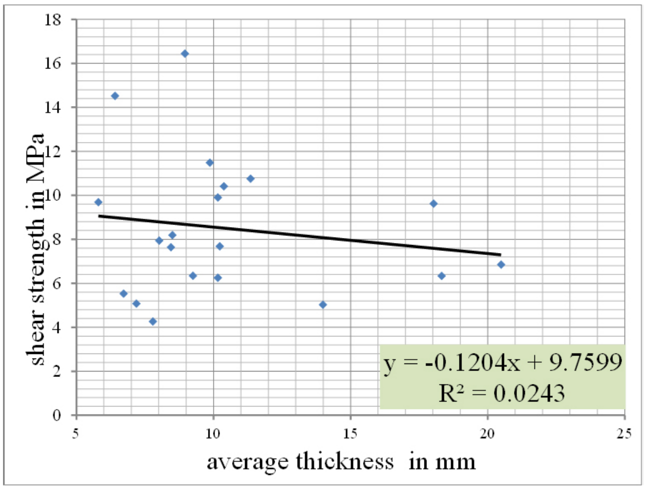

Figure 7: relation between thickness and shear strength

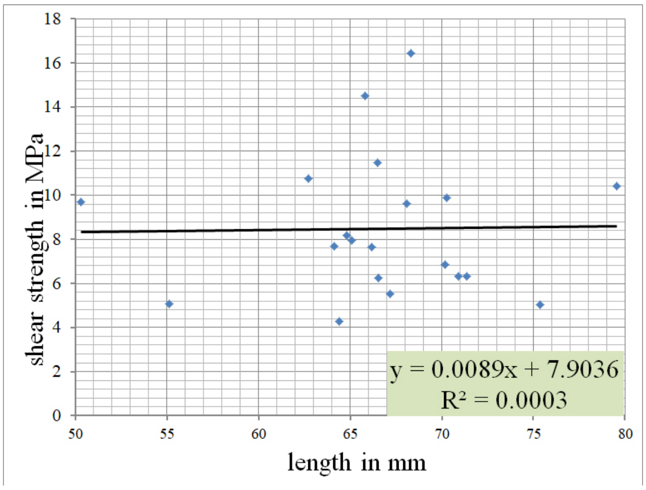

Figure 8: relation between avg. length of specimen and shear strength

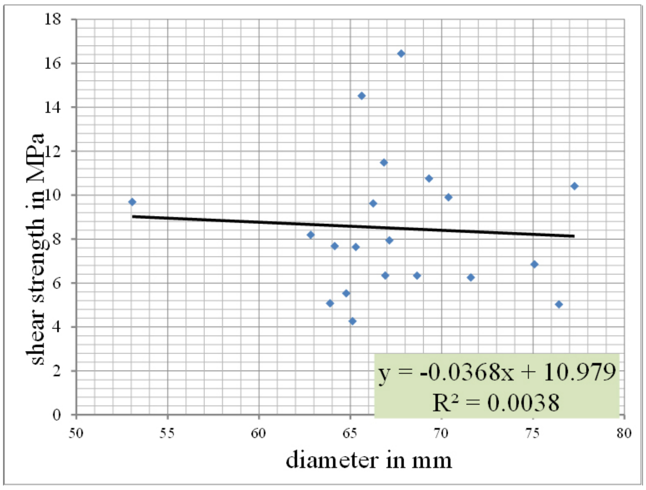

Figure 9: relation between average diameter and shear strength

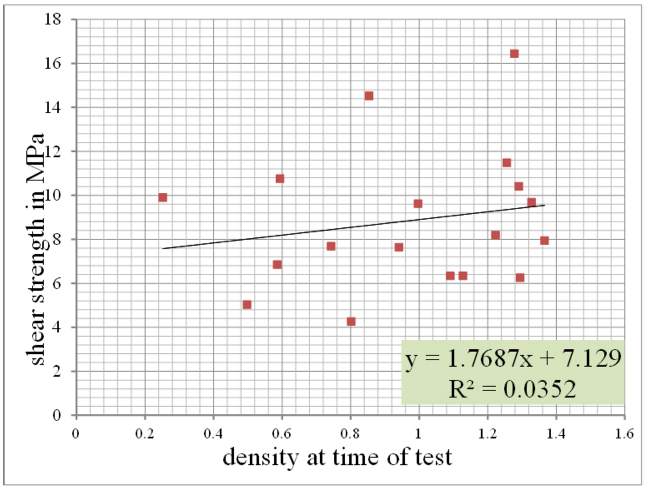

Figure 10: relation between density at test and shear strength

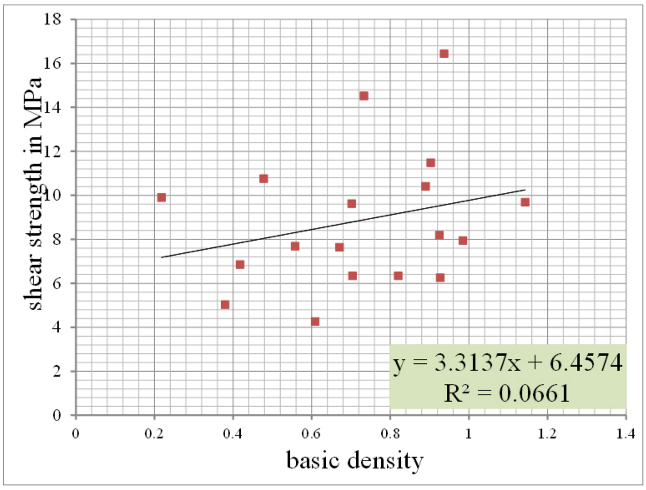

Figure 11: relation between basic density and shear strength

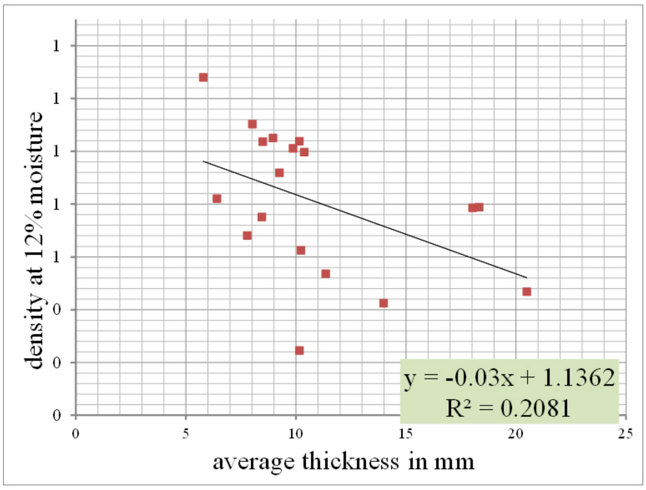

Figure 12: relation between density at 12% moisture content and shear strength

4. Discussion

Relationship seen between shear strengths and moisture content of bamboo specimen emphasize that the increase in moisture content results in decrease in the overall shear strength of bamboo. As suggested by many literatures for different species of bamboo, this relationship has also been demonstrated for Nepalese *Bambusa nutans* too. The R^2 for regression line is low, as there is very less samples from the infinite population of the *Bambusa nutans*. Other factors such as non-uniformity in: age of the bamboo culms, position of the sample in the full culm, etc. may have caused inexact relationships of shear strengths to other parameters, because shear strength is dependent on anatomical structure of the bamboo [9] and age of the bamboo [10] [1]. If possible to maintain consistency among rest of the parameters, the data may would have suggested more exact relation among parameters as bamboo is functionally graded material [11]. Different relationships observed as shown in plots can are adequate to support different claims of literatures about the properties of general bamboo. Strengths seem to be increasing as densities increases. Our observation also suggests that as wall thickness increases, density starts to decline. The wall thickness of specimen was fairly even, same implies for diameter. The 5th and the 95th percentile characteristic value with 75% confidence came out to be 4.67 MPa and 12.7 MPa for the combined tests, which on little modification can be used as design shear strength for commercially available *B. nutans* culms in Nepal.

5. Conclusion

Round bamboo culms which are most likely to be used as axial member are susceptible to splitting due to acting shear forces on them. The characteristic value for shear strength (preferred to be 5th percentile value with 75% confidence, and as per method prescribed by BS ISO 12122-1) was found to be 4.83 MPa, 4.49 MPa and 4.67 MPa respectively for 'air-dry' moisture content, high moisture content and both of them combined. The characteristic shear strength for market-available borax-boric acid treated, most common and mostly used species of Nepalese bamboo, i.e, Bambusa nutans (Maal bans) was found to be satisfactory and comparable to other of the global species.

The variation between the moisture content and shear strength is also demonstrated in data, the declination of the strength-moisture content line was seen as referred by previous literatures. The slope by which it declined was very small, this may be due to the limited number of samples and less diverse samples in Shear strength and moisture content domain.

6. Recommendation

In round bamboo structures, major shear force transfer occurs in the beam-column joint, which is always a critical position regardless of the material used in the structure. So shear failure in round bamboo structure can be studied with different parameters. Variability of shear strength in any particular local species of bamboo can be studied maintaining other parameters consistent. And the characteristic value of 4.83 MPa can be used as a design shear strength for designing bamboo structure using working stress method for Nepalese *Bambusa nutans* as material.

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