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Investigation on Mechanical Properties and Suitability of Highland Bamboo (*Yushania Alpina*) for Use in Structural Truss Members

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Abstract: In responding to the demand for construction materials that are sustainable, eco-friendly, safe and cost effective, several researches were conducted and came up with recommendations including the use of alternative construction materials. In this regard bamboo is taken as one of the alternatives. In Ethiopia there are two bamboo species that are commonly referred as high land bamboo or scientifically as 'Yushania alpina' and low land bamboo or scientifically as 'Oxythenantera abyssinica'. Both of which cover nearly 1.4 million ha of land. Due to their attributes including fast growth, regeneration rate, low cost and strength, different countries are using bamboo for building of different structures and other products like furniture. In order to use the material for construction uses, it is of vital importance that properties of bamboo are determined to explore its potential uses. In this paper Experimental analysis was carried out on high land bamboo culms collected from selected regions of Ethiopia to investigate the compressive, tensile and bending strengths for their suitability as astructural member specifically for roof truss. The samples were collected from three regions in Ethiopia namely, Oromia Regional State (Tikur inchni), SNNPRS (Gurage), and Sidama Regional State. From the tests it was observed that air dried bamboo from the Gurage area (58.12 N/mm^2) had the highest average compressive strength at ambient condition. On the other hand, an oven dried bamboo specimens from the three areas were tested and they showed similar average compressive strengths between 118 and 122 N/mm^2 which were considerably different from the results of air dried bamboo samples. For bending strength Sidama area bamboo (58.53 N/mm^2) showed highest value at ambient conditions. For the tensile strength the Gurage area bamboo (136.13 N/mm^2) had a highest average tensile strength at ambient conditions. A truss using the Tikur inchini area bamboo was designed for G+0 building according to Ethiopian building code standard and built using Tikur inchini area bamboo and tested for stability by applying load of 110 kgs and it was found stable. The material strength of the tested samples for compression and tension were better than the design load of the truss. The research indicated that the highland bamboo can be used as a roof truss which saves cost and environment and provides better strength.

Keywords: Bamboo Culm, Compressive Strength, Bending Strength, Tensile Strength, Roof Truss, Highland Bamboo

1. Introduction

Construction sector is one of the leading economic activities that stretched between the rapidly increasing demands of the built structures to respond to the growing population and the impact the construction materials imposed on the environment. Among the construction activities the demand for housing showed an alarming increase requiring more material consumption [27].

In Ethiopia many of the construction materials are imported. As reported by Ethiopian Ministry of Trade and Industry in 2019 a total of 772,559 tons of construction materials were imported [21]. This showed a decrease from 2013 which was 1,140,782 metric tons [21]. This import volume had its own stress on the foreign currency requirements. On the other hand, in Ethiopia on average

400,000 new housing units are built and an additional 450,000 houses are repaired consuming 6.6 million m^3 of wood per year [17].

An alternative construction material which is eco-friendly, providing maximum strength and durability, resulting in high quality built structure, save time and cost, respond to increasing demand, and easy to use are taken as a criteria to be introduced. Globally, there is an increased interest in use of bamboo. In support of this modern applications are being discovered every day, several of which are based on bamboo's unique physical and mechanical properties.

The interest to use bamboo as a construction material in Ethiopia is increased, but studying its mechanical property and the suitability is not yet matured. This paper tried to investigate the mechanical properties including compressive, tensile and bending strengths of bamboo culms growing in selected regions of Ethiopia. In addition the suitability of the culm for roof truss structure was assessed.

2. Literature Review

2.1. Introduction

One of the grass families belonging to Poaceae (Gramineae), subfamily Bambusoideae that have somehow different characteristics in its growth, size, purpose and distribution is known as bamboo [1].

2.2. Geographical Distribution of Bamboo

Even though different literatures state different number and amount of species and distribution, there are about 1,500 species of bamboo that covers over 36 million ha of world total area [13]. Other literatures amounts it to 14 million ha and some others estimate the number of species to be nearly 2000 [5]. Bamboo is mainly distributed in bamboo zones of Asia, Pacific, Americas and Africa. China had the largest bamboo resources in the world, with more than five hundred (500) species of bamboo [18].

2.3. Ethiopian Bamboo

According to Ethiopian Environment, Forest and Climate change commission estimated in 2019 Ethiopia has 1.47 million hectare of existing bamboo resources with two indigenous species; Yushania alpina (high land bamboo) and Oxytenanthera abyssinica (low land bamboo)[7, 8, 29]. In the other hand The INBAR Production to Consumption study (2018) estimates the availability of 1.1 million ha of bamboo, out of which about 150,000 ha come from highland bamboo and 950,000 ha from lowland bamboo [10]. In addition to the two indigenous species, over 40 species were introduced from different countries via different institutions and development agencies and piloted indifferent geographical locations across the country [8, 11].

Ethiopian bamboo resources concentrated in the Amhara, Benishangul Gumuz, Gambela, Oromia, Southern Nations Nationalities Peoples (SNNPS) (includes Sidama region at the time of study) with the amount of bamboo coverage as shown in figure 1.

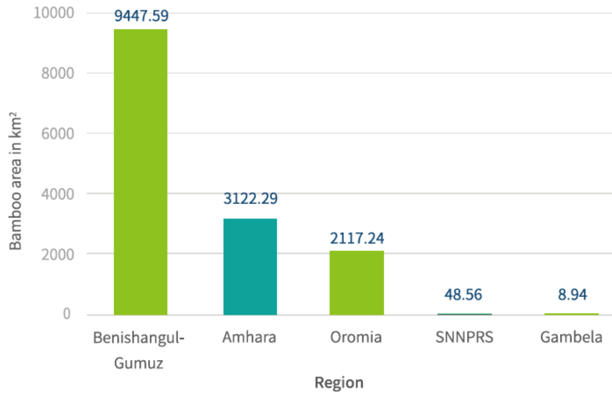

Figure 1. *Ethiopian Bamboo resource by region (source: EFCCC, 2019).*

2.4. Properties of Bamboo

Bamboo is a perennial, hollow woody plant that grows fast and reaches maturity within 3 to 5 years. It has a unique property from its family among species that grows in different parts of the world. The properties can be classified as physical (including, density, fiber content/length, and moisture content) and mechanical (compression, tensile, bending and shear) properties. These properties determine the purpose and suitability of bamboo for different uses. Because of its fast-growing nature, it is an easily renewable raw material that has an attractive and unique appearance and toughness [28].

Many of the properties of bamboo peak at a particular age and then decrease again if the culms are not harvested. In addition to age the area where it grows also affect the property of bamboo.

The highland bamboo which is a monopodial type grows well in mountain and volcanic soils with rainfall ranging from 1250–3000 mm. It grows in a height range of 2–19.5 m with diameter of 5–12.5 cm. it is thin walled with wall thickness ranging from 2 cm at the bottom to 0.3 cm at the top [7]. At maturity the culm of the Ethiopian highland bamboo is hollow [9].

2.5. Uses of Bamboo

With the current emphasis on environmental friendliness and sustainability, natural fibre composites are more preferred over conventional fibre which is normally non-biodegradable [20]. Its potential role and contribution to climate change mitigation, adaptation and resilience building also received promising recognition in the scientific community and relevant international organizations.

Globally, it has 1500 versatile socio-economic uses and environmental/ecological services [19]. It provides construction, food, fodder, handicrafts, furniture, musical instruments, flooring and versatile industry materials, environmental benefits and other services [11].

According to the Food and Agriculture Organization of the United Nations [10] approximately over one billion people worldwide live in traditional bamboo housing, and 2.5 billion people depend economically on bamboo. Atanda (2015) grouped the utilization of bamboo into six major aspects as Construction, Furniture production, Papermaking, Textile, Pharmaceutical usage and Household-items [3]. In addition to this Bamboo has been utilized as a fuel (charcoal, oil, gas produced through pyrolysis), and other ranges of products like chopsticks and table wears.

In Ethiopia it is used for sustenance uses and to produce low-quality products, such as fences, traditional houses, rudimentary furniture, mats and household utensils. Recently, a few industries have started producing bamboo industrial products [8]. Utilizing this resource as a potential input for construction and other purposes is the recent agenda encouraged by the governmental, research and private institutions.

2.6. Bamboo as a Building Material

In the modern world people prefer brick, concrete, and steel as structural and construction materials for modern buildings [15]. Recently due to environmental issues bamboo is becoming a preferred building material and attracted several researchers and designers to work on its utilization [15]. In many parts of the world mainly in Asia, the Pacific Islands and both Central and South America, bamboo is used as a structural and nonstructural component of houses.

The fast-growing, eco-friendly and less energy-consuming nature of bamboo contributes more to promote green construction and wise utilization of natural resources. On the other hand in many countries it is tested and verified to have a capacity to replace steel, aluminum and timber usage for construction purpose [26]. It also reduces construction costs to a reasonable amount compared to other timber and steel structures [27]. The potential number of construction applications has been increased by the recent development of bamboo-based panels. Bamboo architecture has taken a big leap in developing countries in recent years and has become a symbol of eco-friendly design and sustainability led by buildings [22]. It can be applied as a natural product or engineered bamboo after passing some industrial process [8]. Traditional bamboo houses using a bamboo frame and prefabricated houses made of bamboo laminated boards are easy to find in China, India, Thailand and other Asia areas [25]. In Ethiopia many traditional houses of the ancient times including churches and palaces use both full and split bamboo culm as roof to carry the grass roof cover as shown in figure 3. There are also traditional bamboo houses in bamboo growing areas that use split and full bamboo for all housing components (see figure 2).

Figure 2. *Traditional bamboo house in Ethiopia (Source: ttps://www.worancha.com/2015).*

Figure 3. *Emperor Minilik II palace at Entoto with bamboo roof truss (Source: https://www.tripadvisor.com/locationPhotoDirectLink).*

2.7. Mechanical Properties of Bamboo

The mechanical properties of bamboo varies significantly depending on species and conditions like climate, altitude, moisture content, age, and harvest time. The mechanical property of bamboo is highest at the ages of 3 to 5 years and then it starts to decline. For example: the mechanical properties of Guaduaa. k. type bamboo exhibited higher values of strength for 3 and 4-year-old culms [6].

The strength of bamboo is also affected by the moisture content of the specimen. Specimens exhibiting moisture content greater than the free saturation point (FSP) exhibit fairly stable strengths, and those with moisture contents less than the FSP exhibit an increase in strength inversely proportional to the moisture content [2]. Awalluddin et al (2017) conducted compression test on four different bamboo species and found the compressive strength of bamboo was higher at the top part of all bamboo species, followed by middle, and lastly, bottom part [4].

Bamboo has been cited as having a tensile strength similar to mild steel in some cases and influenced primarily by the bamboo fiber volume ratio [6]. Amada et al. (1996, 1997) studied tensile specimens from two-year-old Phyllostachys edulis Riv. (Mousou bamboo) and found that the tensile strength of the bamboo (140-230 MPa) was greater than that of common woods such as fir, pine, and spruce (~30-50 MPa).

A bending test causes compression stresses on the upper part of the bamboo beam, parallel to the fibers, which does not pose a problem for the material. The reduction in both the diameter and wall thickness along the culm also closely matches the reduction in bending moment along the culm. This results in bamboo having an almost constant maximum surface stress along its length when subjected to wind forces [27].

2.8. Bamboo as a Roof Truss

Alternatively due to its hollow form, the high land bamboo is relatively strong; stiff and lends itself easily for roof trusses in the same manner as timber roof trusses. However, bamboo must be treated in order to increase durability. It is not completely straight which can cause problems for the achievement of an even roof surface [16].

The design of the bamboo trusses depends on the quality and strength of the treated culms and on the roofing material and the related roof inclination, whether metal sheeting, thatch or other materials [23]. Much of the deflection of a loaded truss has been found to be due to deformation at the joints [12]. Janssen (1995) developed a truss spanning 8 meters as shown in figure 4.

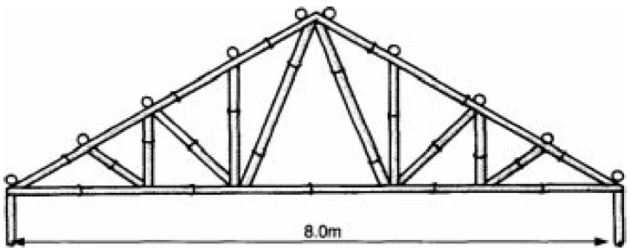

Figure 4. *Janssen bamboo roof truss configuration (Source: Janssen, 1995).*

3. Materials and Methodology

This study attempted experimentally to investigate the mechanical properties (compressive, bending and tensile) of Ethiopian high land bamboo collected from the Tikur inchini (Oromia Region), Gurage zone (SNNPR) and Sidama region through laboratory test.

To conduct this research work: for compression test; procedures, requirements and designs for sampling, testing and expression of results are taken from the ISO standard for testing of bamboo (ISO 22157: 2019). In the case of bending and tension test due to the absence of test facilities in testing laboratories a different sample size and method was used, but results are calculated based on the standard.

3.1. Materials

Air dried matured bamboo culms from Tikur inchini (Oromia region), Gurage (SNNPS region) and from Sidama region are collected and made ready to be tested. The samples are prepared based on the procedures given in ISO 22157.

3.2. Mechanical Properties

3.2.1. Compressive Strength

For compression test 21 specimens from Tikur inchini; 18 specimens from Gurage and 13 specimens from Sidama were taken from the bottom, middle and top part of the bamboo culm with the average length of 70 mm. The diameter and wall thickness of each sample is recorded. The specimens are made ready for testing as shown in figure 5.

Figure 5. *Tikur incinini Bamboo sample for compression.*

The samples taken from the three areas were tested in Ethiopian Conformity Assessment laboratory. After each compression test the samples were tested for moisture content. In addition the compressive strength was measured in two ways. One as it is taken from the sampling area (air dried) to check its status and the second after oven dried with a temperature of 102°C until it loses its moisture. The machine provides ultimate load applied until failure. The compression strength is calculated using formula (1).

$$f_{c,0} = {F_{ult}}/{A} \qquad (1)$$

Where

F_{ult}-is the maximum load at which the specimen fails, in Newton (N);

A-is the cross-sectional area in square millimeters (mm^2).

Figure 6. *Gurage bamboo samples for bending.*

3.2.2. Bending Strength Parallel to the Fibres

This test was used to determine the bending moment at failure and the bending strength parallel to fibres for bamboo culms. Tests specimens were taken from Tikur inchini (7), Gurage (12) and Sidama (7) areas. The length of the specimen was taken 900 mm and 2/3 of the length was put within the loading area. Average wall thickness, δ and average outer diameter, D, of each specimen were measured and recorded. A loading span *a*, of 200 mm is taken in both sides. The test specimens were shown in figure 6.

After reading the ultimate load at failure the bending moment and bending strength was calculated using formula (2) and (3) respectively.

$$M_{ult} = \frac{F_{ult} x a}{2} \qquad (2)$$

Where

F_{ult}-is the maximum applied load (i.e. the total load applied to both load points), in Newton (N);

a-is the shear span which is the distance between the support and the loading point, expressed in millimetres (mm)

The bending strength parallel to the fibres, $f_{m,0}$, shall be calculated from Formula (3)

$$f_{m,0} = \frac{M_{ult} x D}{2 x I_B} \quad (3)$$

Where

M_{ult}-is the ultimate bending moment as per Formula (3), expressed in Newton millimeters (Nmm);

D -is the outside diameter obtained near the point of failure, in millimeters (mm);

I_B -is the second moment of area (or moment of inertia), calculated from the diameter and wall thickness obtained near the point of failure, in millimeters to the fourth power (mm^4).

3.2.3. Tension Strength Parallel to the Fibers

Tension tests were carried out on a suitable testing machine capable of measuring tension load. The grips of the tension machine arranged to ensure that the load was applied concentrically along the longitudinal axis of the test piece, and to prevent longitudinal twisting of the test piece. A total of nine 600 mm long strips of bamboo from each area were taken from the bottom, middle and top part of each culm (figure 7). Wall thickness and width of the specimens were measured and recorded. The tensile strength was calculated from the ultimate load at failure using formula (4).

$$f_{t,0} = \frac{F_{ult}}{A_g} \quad (4)$$

Where

F_{ult} -is the maximum load at which the specimen fails, in Newton (N)

A_g -is the mean cross-sectional area of the gauge portion described in the procedure, in square millimeters (mm^2).

3.3. Suitability of Bamboo as a Roof Truss

To test the suitability of bamboo as a roof truss a two dimensional roof truss of 3 meters long was designed using Ethiopian building code for timber and ES 6416 (design of bamboo structures) and assembled using a positive fitting method as shown in figure 8. Then the truss is placed on a standing structure and loaded at the center and supports to test for stability. The material compressive and tensile strength test results and the design load for a G+0 building was compared.

Figure 7. *Bamboo samples for tensile.*

Figure 8. *Bamboo roof truss for suitability test.*

4. Results and Discussion

The test results are analyzed and discussed in this chapter.

4.1. Mechanical Strength Properties

4.1.1. Compressive Strength of the Three Areas

From the tests conducted on the samples collected from the three areas, various properties are observed. First, compressive, bending and tensile properties of the different parts of air dried highland bamboo culms were analyzed and compared among the three areas at ambient conditions. Secondly, the samples from the three different areas were made to dry to have similar moisture content using electric oven with a temperature of 102°C until moisture was removed. Then the compressive strength values were compared at nearly zero moisture content. The compressive strength distribution of air dried bamboo culms from the three areas is presented in table 1.

From the table (table 1) regardless of other physical properties, generally the bamboo culm from the Gurage area (58.28 N/mm^2) showed higher average compressive strength followed by Tikur inchini (50.11 N/mm^2) and finally Sidama (44.25 N/mm^2).

Table 1. *Compressive strength results of the three area bamboo samples.*

Area	Compressive strength values in N/mm^2					
	Bottom	Middle	Top	Minimum	Maximum	Total Average
Tikur inchini	45.22	52.56	54.02	30.78	71.84	50.11
Gurage	51.88	59.05	63.82	40.19	87.43	58.28
Sidama	41.45	36.89	55.11	30.37	60.99	44.25

Compressive strength values of oven dried bamboo samples were as given in table 2. The results showed that bamboo from the three areas have nearly similar average compressive strength, but the Tikur inchini area bamboo (122 N/mm^2) showed higher value than the other two. The Sidama area bamboo showed a maximum compressive strength of 153.33 N/mm^2 and a minimum value of 78.14 N/mm^2 compared to the others.

Table 2. *Compressive strength of oven dried bamboo.*

	Compressive strength (N/mm^2)		
Area bamboo	**Minvalue**	**Max value**	**Average value**
Tikur inchini	90.52	146.23	122.0
Gurage	80.10	135.49	118.34
Sidama	78.14	153.33	121.10

4.1.2. Bending Strength of the Three Areas

The bending strength results of Tikur inchini, Gurage and Sidama area bamboo culms are shown in table 3. The bending strength of Sidama area bamboo (58.53 N/mm^2) showed higher values followed by Gurage area (57.56 N/mm^2) and Tikur inchini (31.16 N/mm^2).

Table 3. *Bending strength values of bamboo from the three areas.*

Area	**Bending strength values in N/mm^2**					
	Bottom average	**Middle average**	**Top average**	**Minimum**	**Maximum**	**Total Average**
Tikur inchini	25.24	19.18	55.05	9.36	84.82	31.16
Gurage	64.09	49.93	58.65	39.16	89.09	57.56
Sidama	53.84	69.23	54.86	36.83	69.62	58.53

4.1.3. Tension Strength of Bamboo

Tensile strength of a bamboo strips with a length of 600 mm from the three areas was tested and the results were shown in table 4. The result showed that the Gurage area bamboo had the highest average tensile strength of 136.13 N/mm^2 compared to the other two and Tikur inchini has the lowest with strength of 73.26 N/mm^2.

Table 4. *Tensile strength values of bamboo from the three areas.*

Area	**Tension strength values in N/mm^2**					
	Bottom	**Middle**	**Top**	**Minimum**	**Maximum**	**Average**
Tikur inchini	51.77	85.12	82.88	29.56	136.13	73.26
Gurage	132.83	147.07	128.48	69.37	185.10	136.13
Sidama	100.24	70.91	86.05	64.09	126.90	85.73

4.2. Suitability of Bamboo for Roof Truss

Based on the design a roof truss was built using a positive fitting method to connect the joints. It was observed that the roof truss can carry a load of 110 kg without showing any deformation. In addition the designed load in tension was found smaller than the average smaller tension force (73.26 N/mm^2) of Tikur inchini. The compressive strength of all the three areas was found greater than the design compressive strengths of the roof truss.

5. Conclusions and Recommendations

From the analysis of the test results the researcher made conclusions and recommendations.

5.1. Conclusions

Ethiopian bamboo culms have comparable mechanical properties; compressive, bending and tensile strengths that can be used as a structural member. Compressive strength showed an increase from the bottom part to the top part of the culm. The bending strength became higher at the bottom then at the top and lower value was obtained at the middle except Sidama area bamboo. For tensile the middle part had higher strength for Gurage and Tiu inchini, but the bottom from Sidama.

For air dried samples collected from the three areas, at ambient condition bamboo of the Gurage area has higher compressive and tensile strength while the Sidama area bamboo had highest in bending strength, but lowest in compressive strength. Tikur inchini area bamboo is lowest in tensile and bending strength.

For oven dried bamboo samples the Sidama area bamboo showed both maximum and minimum compressive strength than the other areas. But the average compressive strength values of the three areas were nearly similar.

Bamboo culms can be used as a roof truss element with a consideration of proper design and usage of the connection methods. Bamboo roof truss can carry a reasonable load without showing any deformation. The design load of a G+0 building was smaller than the compressive and tension strength of tested bamboo culms.

5.2. Recommendations

Comparing with literature, this finding shows Ethiopian highland bamboo had good mechanical properties. So it should be used in structural use in replacement of timber. The strength a bamboo roof truss had a good indication of its substitute for timber which is a depleting resource. So using bamboo culms as a roof truss for G+0 building is advantageous in having better strength compared to timber. In using bamboo for roof truss care should be taken in selecting the appropriate culm that can provide required strength to carry the design load of the structure. Detail research should be conducted on connection methods and the suitability of bamboo for other structural members.

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