Transactions of the Nigerian Association of Mathematical Physics
Volume 18, (January – December, 2022 Issue), **pp193 –198**
© Trans. of NAMP

DESIGN OF BAMBOO-MADE BICYCLE STRUCTURE

Ebhojiaye R.S. and Eboigbe C.I.

Department of Production Engineering, University of Benin, Benin City.

Abstract

This project designed a Bamboo-made Bicycle structure for the development of a strong and light weight Bicycle. An analytical and experimental investigation was carried out to study the development of a Bamboo-made Bicycle structure. Structural analysis was used for the determination of stresses induced by the action of load on the bicycle. The members of the bicycle were either under the action of compressive force or tensile force caused by the load applied. Using structural analysis and comparison with the average Tensile and compressive strength, the Bamboo frame can withstand the load of a normal steel frame bicycle. The reduction in the weight was due to the use of the Bamboo for the design. Before the assembling of the Bamboo made bicycle structure, an Engineering drawing of the bicycle with its dimensions were made. The bicycle was assembled and performance test were carried out. The optimum values for the tensile and compressive strength were 49.89MPa and 94.3MPa respectively. The bamboo bicycle can carry a maximum load of 3525.8879kg and the weight of the developed Bamboo made bicycle reduced compared to the steel bicycle by a factor 0.6244V.

***Keywords*:** Bamboo, Compressive force, tensile force, Bicycle, frame.

1. Introduction

Bicycles serve as a means of reducing the challenges of traffic congestion in urban areas. They also provide rural dwellers with cheap access to markets and services. They do not use premium motor spirit and do not pollute our environment .Moreover, pedaling is a good exercise for healthier and better life [1].

In rural areas in Nigeria, there is large interest in bicycle transportation. The common bicyles were developed using aluminum. Aluminum was used because it possesses light weight and can increase the frame efficiency by about 3 percent above that of a comparable steel frame [2].

Climate change and pollution are the effects of vehicles that burn fossil fuels. To reduce these problems, manufactures are focusing on the sustainable development, reduction of the energy consumption and preserving the natural environment. This has led to the development of the natural materials like Bamboo [3].

Bamboo is a composite material which grows abundantly in most of the tropical countries. It is considered a composite material because it consists of cellulose fibers imbedded in a lignin matrix. Cellulose fibers are aligned along the length of the bamboo providing maximum tensile flexural strength and rigidity in that direction [4]. Over 1200 bamboo species have been identified globally. Bamboo has a very long history with human kind. Bamboo chips were used to record history in ancient China [5]. Bamboo is also one of the oldest building materials used by human kind [6]. It has been used widely for household products and extended to industrial applications due to advances in processing technology and increased market demand. In Asian countries, bamboo has been used for household utilities such as containers, chopsticks, woven mats, fishing poles, cricket boxes, handicrafts, chairs, etc. It has also been widely used in building applications, such as flooring, ceiling, walls, windows, doors, fences, housing roofs, trusses, rafters and purlins; it is also used in construction as structural materials for bridges, water transportation facilities and skyscraper scaffoldings. There are about 35 species now used as raw materials for the pulp and paper industry. Massive plantation of bamboo provides an increasingly important source of raw material for pulp and paper industry in China [7].

There are several differences between bamboo and wood. In bamboo, there are no rays or knots, which give bamboo a far more evenly distributed stresses throughout its length. Bamboo is a hollow tube, sometimes with thin walls, and consequently it is more difficult to join bamboo than pieces of wood. Bamboo does not contain the same chemical extractives as wood, and can therefore be glued very well [8]. Bamboo's diameter, thickness, and inter-nodal length have a macroscopically graded structure while the fiber distribution exhibits a microscopically graded architecture, which lead to favorable properties of bamboo [9]. As a cheap and fast-grown resource with superior physical and mechanical properties compared to most wood species, bamboo offers great potential as an alternative to wood [10].

Correspondence Author: Ebhojiaye R.S., Email: Christopher.eboigbe@uniben.edu, Tel: +2348036212968, +2348035106026 (ECI)

These "chambers" or "nodes" also add to the bamboo's resistance to damage due to impact. As a bicycle frame construction material, these segments can help to dampen road vibrations throughout the frame structure while still providing the stiffness required for proper handling and efficient power transfer [11].

The average ultimate tensile strength of bamboo is between 30-350MPa and carries an average density of 0.4(g/cm3). Unlike wood, bamboo has no rays or knots, allowing it to withstand more stress than comparable woods throughout the length of each stalk.This strength is similar to that of aluminum, a material commonly used to make bicycles. Aluminum has an ultimate tensile strength of 310MPa, but an average density of 2.7(g/cm3) [12]. Bamboo is an equally strong material, but much lighter than aluminum, making it ideal for bicycle frames. Though, bicycles are a staple of human transportation, in both rural and urbanized areas, bamboo bicycles not widely used. However, with the advent of Green movement, bamboo is being used again, primarily for high-end racing and touring bicycles. Bamboo bikes are entering the market as low cost alternatives to relatively expensive and unsustainable aluminum and metal bikes.
This research therefore reports the design of a bamboo-made bicycle structure for the production of a low cost, strong and light weight bicycles.

2. Methodology

Bamboo was selected for the production of the frame of the bicycle, because it has great tendency to absorb shocks, it has very good tensile strength and modulus of elasticity and also eco-friendly [13, 14]. Other reasons are that bamboo is readily available in Nigeria at very low cost when compared to aluminum and other metals .It is flexible, tough and possesses a light weight.

Table 1: Mechanical Properties of Bamboo [15]

Property		**Mean**	**Standard Deviation**	**Coefficient of Variation (%)**
Moisture	Dry basis	10.76(%)	1.35	12.55
Density	Oven dry	590 kg/m^3	0.10	16.95
Compressive strength	With nodes	48.89 MPa	8.93	17.89
	Without nodes	51.68 MPa	7.95	15.38
Tensile strength	With nodes	94.3 MPa	19.10	20.20
	Without nodes	117.9 MPa	9.70	8.20
Bending strength	With nodes	107.0 MPa	21.50	20.10
	Without nodes	137.7 MPa	15.30	11.10
Modulus of Elasticity (tensile strength)	With nodes	3002.3 MPa	567.30	18.90
	Without nodes	3594.0 MPa	649.80	18.00
Modulus of Elasticity (compressive strength)	With nodes	7268.1 MPa	2889.20	39.80
	Without nodes	10405.3 MPa	3525.5	33.90

2.1 Design Specification

For this study, a bicycle was procured, disassembled and its dimensions taken. This measured data were used as the specification for preparing the bamboo that will be used for the frame. The following are the dimensions obtained:
Length of seat tube = 570mm
Outside Diameter of seat tube = 30mm
Inside diameter of sear tube = 4mm
Effective Top tube length = 540mm
Outside diameter = 30mm
Inside diameter = 4mm
Length of chain stay = 390mm
Outside Diameter of chain stay = 20mm
Inside diameter of chain stay = 4.5mm
Length of Down tube = 570mm
Outside Diameter of Down tube = 30mm
Inside diameter of Down tube = 4mm
Seat tube angle = 70°
Wheel base = 354mm

Fork rake = 50°

From the dimensions obtained the cross sectional area of the bicycle frame (i.e. seat tube, top tube, and down tube) was obtained as 694mm^2 using equation (1).

$$A = \frac{\pi(D^2-d^2)}{4} \quad (1)$$

Also, the cross sectional area of the chain stay, A_c was determined as 298.4mm^2

2.2 Design Calculations

To resolve the internal forces acting on the bamboo frame in each member of the idealized bike frame, all the joints were assumed as hinges as shown in Figure 1.

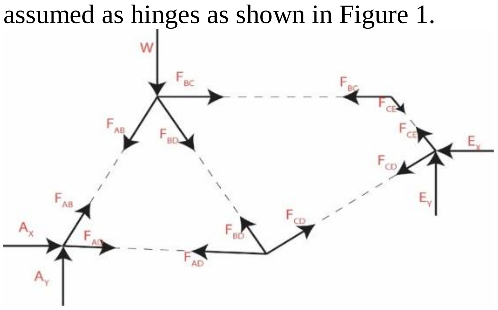

Figure 1: Free Body Diagram of the Bicycle Frame

Unknowns: Force in each member; $F_{AB}, F_{AD}, F_{BC}, F_{BD}, F_{CD}, F_{CE}$. Reaction forces; A_X, A_Y, E_X, E_Y.

Equations: $\sum F_X = \sum F_Y = 0$ (2)

$\sum A_X$; $F_{AB}\cos 62° + F_{AD} + A_X = 0$ (3)

$\sum A_Y$; $F_{AB}\sin 62° + A_y = 0$ (4)

$\sum B_X$; $F_{BC} + F_{BD}cos76° - F_{AB}cos56° = 0$ (5)

$\sum B_Y$; $-F_{AB}sin56° - W - F_{BD}sin76° = 0$ (6)

$\sum D_X$; $F_{CD}cos46° - F_{BD}cos70° - F_{AD} = 0$ (7)

$\sum D_Y$; $F_{CD}sin46° + F_{BD}sin70° = 0$ (8)

$\sum C_X$; $F_{BC} - F_{CE}sin26° = 0$ (9)

$\sum C_Y$; $-F_{CE}cos26° = 0$ (10)

$\sum E_X$; $-F_{CE}cos64° - F_{CD}cos40° - E_X = 0$ (11)

$\sum E_Y$; $F_{CE}sin64° + F_{CD}sin40° - E_Y = 0$ (12)

Solving the equations simultaneously, From eqn. (10),

$F_{CE} = 0$

From eqn. (11),

$F_{BC} = 0$

From eqn. (5),

$F_{BD}cos76° = F_{AB}cos56°$

From eqn. (6),

$$F_{AB} = \frac{-W}{3.07}$$

$F_{\boldsymbol{BD}} = -0.75W$

From eqn. (8),

$F_{CD} = 0.98W$

From eqn. (4),

$A_Y = 0.2876W$

From eqn. (7),

$F_{AD} = 0.9372W$

From eqn. (3),

$A_X = -1.09W$

From eqn. (11),

$E_X = -0.75W$

From eqn. (12),

$E_Y = 0.6299W$

2.3 Design for Reduction of Weight

Malppan and Sunny [16] stated that the main part of the bicycle is the frame as shown in Figure 2. The core is made of metal tubes which are welded together. Lowering the weight of bicycles helps save power. The use of bamboo on the bicycle frame reduces the overall weight of the bicycle. At a constant speed a large weight reduction saves only a negligible amount of power but for climbing steeply, any weight can be felt directly. A reduction of the total system weight (weight of bicycle + weight of rider) will save considerable percentage of power.

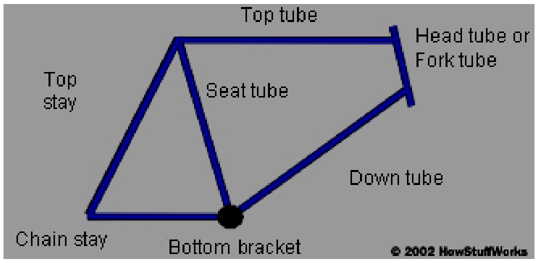

Figure 2: The Bicycle Frame

2.3.1 Performance Modeling

In carrying out the performance evaluation of the bamboo bicycle, parameters such as body mass, height, saddle position of the cyclist, type and aerodynamic characteristics of the bicycle and cyclist's apparel, rolling resistance of the surface, wind, temperature, air density, humidity were considered. The power was determined using equation (13).

$P = 0.7697\ K\ [0.00953\ M_t\ V + 0.0075V^2 + K_1(A_f)\ 0.007551V^3]$ (13)

Where, P = power (W),
K = constant describing track characteristics and rolling resistance,
M_t = mass of cyclist and bike (kg),
V = speed (km/hr),
K_1 = constant describing aerodynamic factors,
A_f= frontal area of the cyclist.

The A_f value was determined using this relationship, $A_f = 0.0293 \times height^{0.725} \times weight^{0.425} + 0.0604$, and the correction factor for team pursuit is 0.7697.

The constant K, which is usually around 1, quantifies the influence of aerodynamic factors and is calculated as shown in equation (14):

$K_1 = K_d \times K_{po} \times K_b \times K_c \times K_h$ (14)

Where, K_d = density ratio (1 at sea level and 0.78 at 2500m altitude);
K_{po} = position of the cyclist on the cycle (1.08–1.18 for standard position, 1 for standard aero position);
K_b = bicycle-related factor (1 for standard cycle, 0.93 for aerodynamically optimized track cycle);
K_c = clothing (1 for aerodynamic skin suit, 1.09 for long sleeve jersey);
K_h =helmet (1 for aero time-trial helmet, 1.025 for conventional cycle helmet.

2.5 Performance Test

The bought out steel framed bicycle was used as control in order to do the comparative performance evaluation of the produced bamboo framed bicycle. In carrying out the performance test on the bamboo framed bicycle, the following data were obtained:

Mass of bamboo framed bicycle = 10.13kg
Mass of steel framed bicycle = 12.25kg
Also the mass and height of the rider were assumed to be 75kg and 1.84m respectively.
∴ Weight of rider (W) = mg = 735.75N
Therefore, the force of tension and compression on each member were determined as follow:

$F_{CE} = 0$
$F_{BC} = 0$
$F_{AB} = \frac{-W}{3.07} = -239.65798N$

The negative sign signifies that the direction of the force should be reversed.

$F_{BD} = -0.75W = -0.75 \times 735.75 = -551N$
$F_{CD} = 0.98W = O.98 \times 735.75 = 721.035N$

$F_{AD} = -0.9373W = -0.9372 \times 735.75 = -698.544N$
$A_Y = 0.2387W = 0.2876 \times 735.75 = 211.528N$
$A_X = -1.09W = -1.09 \times 735.75 = -801.967N$
$E_X = -0.75W = -0.75 \times 735.75 = 551.8N$
$E_Y = 0.6299W = 0.6299 \times 735.75 = 463.449N$
Therefore, F_{AB}, F_{BD} are tensile loads.
F_{CD}, F_{AD}, are Compression loads.
Tensile load at seat tube = $\frac{F_{BD}}{Area\ of\ seat\ tube} = 79.394$kN/m
Compression load at down tube = $\frac{F_{CD}}{Area\ of\ down\ tube} = 1038.96$kN/m
Compression load at chain stay = $\frac{F_{AD}}{Area\ of\ chain\ stay} = 2340.97$kN/m
Since, $F_{CE} = F_{BC} = 0$, that means that there no tensile or compressive load on the top tube.
In other to appreciate the reduction in mass, we calculated the power required by the cyclist to cause the bicycle to move at specific speed.
P = 0.7697 K [0.00953 M_t V + 0.0075V^2 + $K_1(A_f)$ 0.007551V^3]

(a) For Steel Bicycle
Take k=1, $M_t = 75 + 12.25 = 87.25kg$, $K_d = 1$, $K_{po} = 1.18$, $K_b = 1$, $K_c = 1$, $K_h = 1.025$
K_1 = 1 × 1.18 × 1 × 1 × 1.025 = 1.2095
A_f = = 0.0293 × $height^{0.725}$ × $weight^{0.425}$ + 0.0604 = 0.0293 × $1.84^{0.725}$ × $750^{0.425}$ + 0.0604 = 0.8203
P = 0.7697× 1 [(0.00953 × 87.25 × V) + 0.0075V^2 + 1.2095(0.8203) 0.007551V^3]
P = 0.64V + 0.00577$V^2 + 0.00576V^3$

(b) For Bamboo Bicycle
Take k=1, $M_t = 75 + 10.13 = 85.13kg$, $K_d = 1$, $K_{po} = 1.18$, $K_b = 1$, $K_c = 1$, $K_h = 1.025$
K_1 = 1 × 1.18 × 1 × 1 × 1.025 = 1.2095
A_f = = 0.0293 × $height^{0.725}$ × $weight^{0.425}$ + 0.0604 = 0.0293 × $1.84^{0.725}$ × $750^{0.425}$ + 0.0604 = 0.8203
P = 0.7697× 1 [(0.00953 × 85.13 × V) + 0.0075V^2 + 1.2095(0.8203) 0.007551V^3]
P = 0.6244V + 0.00577$V^2 + 0.00576V^3$
Decrease in power at a particular speed is caused by the factor "0.6244V" which is solely influenced by the reduction in mass of the bicycle with other conditions kept constant.

Figure 3: Bamboo made Bicycle Structure

3. Results and Discussion

The mechanical properties of the bamboo were gotten by investigation. An easily sourced bamboo (Bambusa Vulgaris) was used for the project. The internal stress of tension and compression caused by the action of the weight of the rider were calculated. The corresponding stresses were also calculated. The value of average tensile and compressive strength gotten from the experiment was compared with that calculated from the analysis of the free body diagram of the frame under the action of the rider's weight only. It was observed that the average maximum tensile and compressive strength of the bamboo exceeded the values obtained from literature due to the action of the rider's weight.
Compressive strength of bamboo without nodes = 49.89MPa
Tensile Strength of bamboo without node = 94.3MPa
Maximum weight to be carried by a bamboo bicycle = 49.84 $\times\ 10^6\ \times\ 694\ \times\ 10^{-6}$ = 34588.96N = 3525.8879kg.

4. Conclusion

In this study, easily sourced light weight Bamboo was utilized for the development of a much cheaper Bicycle. This could bring about a cleaner and greener environment. The construction and installation of the bamboo framework proved to be fully viable and does not demand a large investment.

In addition, the obtained tensile strength value of the Bamboo (Bambusa Vulgaris) in this research is higher than the tensile strength of some aluminum alloys. This shows that bamboo is a very vital engineering material in the development of strong and light weight machines.

5. References

[1] Anuj K.J, Feras, H.M., Gupta, S. J. (2017): "Design and Fabrication of Bamboo Bicycle". International Journal of Advance Research and Innovation, Volume 5, Issue 3 , pp. 347-348.

[2] Hughes, K., and Hull, M.L(1977).: Efficiency of aluminum Bicycle Frames. Department of Mechanical Engineering report, University of California, Davis.

[3] Penava, F.(2014): *Application of natural materials in vehicles*, In Croatian, Faculty of Mechanical Engineering and Naval Architecture, Zagreb.

[4] Lakkad, S.C. and J.M. Patel,1980. Mechanical propertiesof bamboo, a natural composite. Fiber Sci. Technol.,14: 319-322.

[5] Wang D, Shen SJ (1987) Bamboos of China. Timber Press, Portland, Oregon.

[6] Abd.Latif, M., T. Wan, A. Wan and A. Fauzidah, 1990.Anatomical Features and Mechanical Properties of three Malaysian bamboos. J. Trop. Forest Sci., 2:227-234.

[7] Ogunsile, B.O and C.F. Uwajeh (2009). Evaluation of pulp and paper potentials of a Nigerian grown Bambusa vulgaris. World Applied Science Journal 6(4) 536-541.

[8] Janssen, J.A.. 1995. Building with bamboo (second edition). Intermediate Technology Publication Limited, London. pp. 65.

[9] Amanda, S., Munekata, T., Nagase, Y., Ichikawa, Y., Kirigai, A., and Zhifei, Y (1996): The mechanical structures of bamboos in viewpoint of functionally gradient and composite materials. J Com Mater; 30(7): 800-19.

[10] Li, Xiaobo, (2004):"Physical, chemical, and mechanical properties of bamboo and its utilization potential for fiberboard manufacturing" (2004). *LSU Master's Theses*.

[11] Thite, A.N, Gerguri, S, Coleman, F, Doody, M, Fisher, N (2013): Development of an experimental methodology to evaluate the influence of a bamboo frame on the bicycle ride comfort. Veh Syst Dyn 51(9):1287–1304.

[12] ASM Aerospace Specification Metals, I. Aluminum 6061-T6; 6061-T651 [Online]. Pompano Beach, Florida: ASM Aerospace Specification Metals, Inc. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6 2015].

[13] Fierro, J. P. A., Fierro, J. L. A. and Suárez, H. E. J. (2019) "Structural Evaluation of Bamboo Bike Frames: Experimental and Numerical Analysis". www.intechopen.com. Assessed: 13th November 2020.

[14] Bhonde, D., Nagarnaik, P. B., Parbat, D. K. and Waghe, U. P. (2014) "Physical and Mechanical Properties of Bamboo (Dendrocalmus Strictus)". International Journal of Scientific & Engineering Research, vol. 5(1): pp. 455 – 459.

[15] Mbuge, D.O., "Mechanical properties of bamboo (Bambusa vulgaris)" (2000). http://en.m,wikipedia.org/wiki/Bamboo_bicycle.(15/11/2019).

[16] Malppan, J and Sunny, T (2015): A Review on Design Developments in Bicyclcle.. International Research Journal of Engineering and Technology (IRJET), Volume: 02 Issue: 03, pp.1794-1799