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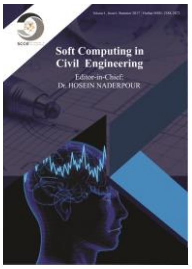

Modeling of Compressive Strength Characteristics of Structural-sized Afara (*Terminalia superba*) and Babo (Isoberlinia *doka*) Timber Columns Using Constant Failure Rate (CFR) Model of Reliability

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ABSTRACT

This paper investigated the reliability of the Structural-sized Afara and Babo timber species as column materials. The work centers on the compressive strength characteristics of Nigerian Afara (*Terminalia superba*) and Babo (*Isoberlinia doka*) timber column of nominal lengths 200, 400, 600 and 800 mm and a nominal width and thickness of 50 mm by 50 mm. The steps involved collection and conditioning of Afara and Babo timber species, preparation of test specimens, determination of physical properties such as moisture content and density, determination of compressive strengths using varying heights of 200, 400, 600 and 800 mm and derivation of continuous column design equations. Forty test samples were used in all the tests carried out. Afara and Babo have an average density of 509.80 and 849.67 kg/m^3 respectively. Moisture content of both species less than the maximum recommended value of 20 % and the average strength at yield of Afara and Babo are 19.99 and 30.96 N/mm^2. The derived continuous equations for design of Afara column and Babo column are $\boldsymbol{\sigma = 16.992e^{0.0039\lambda}}$ and $\sigma = \boldsymbol{32.031e^{-0.001\lambda}}$ respectively. The results of the reliability analysis show that Afara and Babo timber species have reliability index of **0.63** and **0.64** respectively for a service life of **50** years, assuming other serviceability conditions are met. This design procedure is distinct and more effective than the usual procedure of classification of compression members as short, intermediate and long. The paper therefore recommends the adoption of these equations for the design of compression members from these timber species in Nigeria.

1. Introduction

Timber is a natural structural material from matured trees which serves various purposes in construction and furniture industry [1]. Timber is the oldest and widely used construction material. It is used in various structural forms such as railway sleepers, columns, beams, joists, trusses and so on. The strength of a timber depends on its species and the effects of certain growth characteristics [2]. It is one of the few natural and renewable construction materials that exists but has its limitations in general use for construction, carpentry and upholstery [3]. Also, timber is an organic material and thus is subject to deterioration with time [4]. Structural timbers are timbers used in framing and load-bearing structures, where strength is the major factor in its selection and use [5]. Nigeria is a country with an abundant timber [6]. If this natural resource is properly utilized, it will of great benefit to the country in terms of reduction in the cost of construction [1]. The common names of Afara in Nigeria is Yoruba (Afara), Nupe (Eji), Igbo (Edo), Efik (Afia eto) and that of Babo is Yoruba (Babo), Nupe (Baborochi), Hausa (Doka), Tiv (Mkovol).

The main characteristic of these timber species under investigation is their buckling characteristics when subjected to compressive load. According to [7], buckling is a mode of failure that generally results from structurally unstable member due to compressive action on the said member and it depends on the geometric properties of the member. This study concerns about the current trends and integration of advanced technologies to suit the available climatic, human and natural resources to solve the problem of transportation, by making cheaper, better and more reliable structural system in highways [8]. Environment conditions as well as the soil affect the growth of trees and their strength properties. Since most of the strength properties of the timber species recorded in International Standards were based on timber obtained from trees in those areas and the laboratory tests were conducted there as well. Therefore, there is need to determine the strength properties of the locally available timber species and verify their structural reliability in order to prove their degree of structural performances with time [6].

Reliability, R(t) of an item is defined as the ability of an item to perform a required function under stated conditions without failure for a stated period of time [9]. Ghasemi & Nowak [10] stated that, Reliability is often understood to equal the probability that a structure will not fail to perform its intended function. Reliability-based designs are efficient because they make it to achieve either to design a more reliable structure for a given cost and to design a more economical structure for a given reliability. Reliability coefficients ranges from 0 to 1, with higher coefficients indicating higher levels of reliability. However, reliability specifically measures the consistency of an item. According to [11], reliability index using constant failure rate (CFR) model is as given in equation (1):

$$R(t) = e^{-\lambda t} \quad (1)$$

Where:

R(t) = reliability index; λ = constant rate of failure; t = variable time and the failure rate (λ) is express as in equation (2):

$$\lambda = \frac{1 - d}{T} \quad (2)$$

Where: T is the time (years), expected life span of timber, and d: the average compressive strength rate.

Nowak [12] defines structural reliability as the probability that a structural system will satisfy the purpose for which it was designed and efficiently serve the period for which it was designed to without attaining a given limit state. Structural reliability and probabilistic methods have gradually grown to be important in modern structural engineering practice, especially when it involves naturally occurring materials like timber. Structural reliability could currently be used in the formulation of new generation design codes, evaluation of existing structures and probability risk assessment. Ghasemi & Nowak [13] established an optimization procedure to determine the target reliability for structures with consideration of the construction cost, failure cost, maintenance cost, structural life-time, discount rate, time-dependency of the load and resistance, and structural important factor. The contour concept approach was adopted to establish the above relationship. Part of the Objectives for structural design is to fulfill certain performance criteria related to safety and serviceability. One of such performance criteria is usually formulated as a limit state, that is, a mathematical description of the limit between performance and non-performance [14]. Parameters used to describe limit states are loads, strength and stiffness parameters, dimensions and geometrical imperfections; since the parameters are random variables, the outcome of a design in relation to limit state is associated with uncertainty [15]. A significant element of uncertainty is also introduced through lack of information about the actual physical variability.

The aim of this study is to evaluate the compressive strength characteristics of structural-sized Nigerian grown Afara and Babo timber species columns using constant failure rate reliability method. The objectives are: to conduct experiments on the Nigerian Afara and Babo timber species; to derive continuous column design equations for the Nigerian Afara and Babo timber species as column structural material; to estimate the reliability of the Nigerian Afara and Babo timber species; and to promote our locally available and affordable structural material.

2. MATERIALS AND METHOD

Material procurement – *Terminalia superba* (Afara) and *Isoberlinia doka* (Babo) timber species were bought from Tanke, Odo-Okun and Saboline sawmills in Ilorin, Kwara State, Nigeria. These were naturally seasoned for seven months in order to reach moisture content equilibrium environmentally. The natural seasoning were adopted. The timber samples were prepared and tested in accordance with [16]. Test for physical and mechanical properties of structural timbers at the Wood section of the Civil Engineering Department, University of Ilorin, Nigeria. Timber lengths of 50 mm x 50 mm section obtained from each sawmill was cut into lengths 200, 400, 600 and 800 mm. A maximum height of 800 mm was used due to the limited height of the testing machine. The physical property tests of the timber species was carried out at the structural laboratory of Civil Engineering Department, University of Ilorin, while the mechanical strength test was carried out using a Universal Testing Machine (UTM) of capacity 300 kN at the Agricultural and Biosystems Engineering Laboratory at University of Ilorin, Kwara State, Nigeria.

Physical property tests

Moisture Content - In Accordance with [17] immediately after each mechanical test has been conducted, a small sample for determination of moisture content was cut from each test piece. The sample size was 50 x 50 x 50 mm and consists of a transverse section from near the point of fracture. The sample was weighed and then dried in an oven at a temperature of 103 ± 2 °C (217 ± 4 °F) until the weight is constant. The loss in weight expressed as a percentage of the final oven-dry weight is taken as the moisture content of the test piece.

Percentage Moisture content, (m.c) is given as:

$$m.c.\% = \frac{W_a - W_0}{W_0} \, x \, 100\% \quad (3)$$

Where: W_a = Air-dried weight of sample at test in grams, W_0 = Oven-dried weight of sample in grams.

Density - Density of a material is the ratio of the mass to the volume. In the 50mm x 50mm standard given by [17], all test pieces weight and dimensions were determined before test. The density is given as:

$$\rho = \frac{W_a}{V_a} = \frac{W_a}{BxDxH} \quad (4)$$

Where: ρ = density in kg/m^3, B = Breadth in cm, D = Depth in cm, H = height in cm, W_a = Air-dry weight of sample at test in grams (g), V_a = Air-dry volume of sample at test in cubic meters (m^3).

Mechanical property test

Compressive Strength - Compressive strength test was carried out using a Testometric Universal Testing Machine. The following procedures were carried out:

i. The timber was cut into various sizes (200, 400, 600 and 800mm); twenty samples for each of the sizes and then labeled.

ii. The machine height was now adjusted to the sizes of the specimen. Then the timber was fixed for loading.

iii. The speed of the test was calculated according to [17] standard as 13.020, 26.040, 39.060 and 52.075mm/min for the length 200, 400, 600 and 800 mm respectively.

iv. The nominal length, the test speed, weight, breadth, width of the samples was inputted into the computer.

v. The machine was started and load deflection curve can be seen on the computer, the machine was stopped when the sample fails or when the curve starts to deflect downward.

vi. The buckling was measured, and the sample taken out of the machine.

vii. The steps were repeated for the remaining samples.

viii. From the load deflection curve obtained after the test, the stress and strain is calculated

$$\text{Stress, } \sigma\ (\mathrm{N/mm^2}) = \frac{P}{A} \quad (5)$$

$$\text{Strain, } \varepsilon\ (\%) = \frac{\Delta \mathrm{H}}{H} \quad (6)$$

- Member slenderness was calculated as follows:

$$\text{Slenderness ratio, } \lambda = \frac{\mathrm{Le}}{\mathrm{r}} \quad (7)$$

Where: Le = 1.0L, $r = \sqrt{\frac{I}{A}}$, $I = \frac{BD^3}{12}$, A = B*D and

λ = Slenderness Ratio, Le = effective length, r = radius of gyration, I = moment of inertia, A = cross-sectional area, L = Length, B = Breadth, D = Depth.

3. RESULTS AND DISCUSSIONS

Density - The density of an air-dried timber has a direct relationship with the strength of the timber. Hence, the higher the density the higher the strength of the timber and vice versa. The average density of *Terminalia superba* (Afara) and *Isoberlinia doka* (Babo) are 509.80 and 849.67 kg/m³ respectively as presented in Table 1. When compared with Afzelia bipindensis (Apa) and Lannea schimperi (Opon) obtained by [18] the values of 652.74 and 472.60 kg/m^3, this show that Afara is more denser than Opon but less densed to Apa. However, Babo is denser than both Apa and Opon. Also, comparing the result with those of [19], Afara has a lesser density when compared with Albizia, Ekhimi, Ekki and Opepe with density values of 690, 912, 997 and 776 kg/m^3, respectively, whereas Babo was denser than Albizia. This implies that Babo has higher yield strength than Afara. According to [20], Afara can be classified as medium wood whereas Babo is hardwood.

Table 1: Average density of timber species

Specie	Average density (kg/m^3)	
	Afara	Babo
Minimum	376.23	792.74
Maximum	599.83	895.11
Mean	509.80	849.67
Standard deviation	128.68	75.63
COV (%)	12.00	8.85
95% Confidence limit	453.41≤x≤566.20	816.52≤x≤882.82
99% Confidence limit	435.68≤x≤583.92	806.11≤x≤893.23

Moisture content - The average moisture content for Afara and Babo were 14.32 and 15.88 % respectively as presented in Table 2. This result is satisfactory, since it is less than the maximum recommended moisture content of 20 % for an air-dried sample. At this moisture content the likelihood of decay of the timber is greatly reduced. The equilibrium moisture contents (EMC) obtained for both Afara and Babo are both lesser than the Fibre Saturation point (FSP) as stated by [21]. By comparing the moisture contents obtained with that obtained for Neem tree and Negro Pepper by [22] as 12.59 and 16.70 %, this implies that Afara and Babo has higher moisture content than Neem Tree but lesser than Negro Pepper. Also, the values of moisture contents obtained are higher than that of Igba and Somi whereas, lesser than that of Emi-Gbegi and Adere obtained by [23] as 10.59, 13.71, 24.28 and 22.34 %, respectively.

Table 2: Average moisture content of Afara and Babo timber

Specie	Average moisture content (%)	
	Afara	Babo
Minimum	12.48	14.98
Maximum	16.32	17.63
Mean	14.32	15.88
Standard deviation	2.89	5.46
COV (%)	11.45	15.26
95% Confidence limit	13.05≤x≤15.59	13.49≤x≤18.27
99% Confidence limit	12.66≤x≤15.99	12.74≤x≤19.03

Failure modes

A structural size timber column will normally fail by buckling, compression or a combination of both buckling and compression depending on the ratio of its height to its cross-sectional dimension. From the test carried out, it was observed that all 200 mm samples failed by crushing, while the 400, 600 and 800 mm samples fail by buckling. The minimum and maximum shortening for Babo timber was 5 mm for a height of 400 mm and 21 mm for a height of 800 mm, while that of Afara timber was 7 mm for 400 mm height and 30 mm for 800 mm height. This re-affirms the previous deduction that Babo is stronger than Afara, since it experiences lesser lateral deflection. The compression failure of the 200 mm samples was expected as it is the standard dimension for compression test.

Relationship between Mean Stress at yield, Young's Modulus and slenderness ratio

Slenderness is usually given as the ratio of the effective height to the radius of gyration of a compression member. The effect of geometry on strength is expressed in terms of the member's slenderness. For a compression member like column, as the member slenderness increases, the mean yield stress decreases. From the results presented in Table 3, it was observed that the average yield stress of both timber species decreases with increase in height. An exception is Opon timber with 400 mm height having a lower average yield stress than the 600 mm height. This may be due to defects in the timber sample.

Table 3: Slenderness ratio, Stress @ Yield and Young's Modulus relationship for Afara and Babo

Mean Height (mm)	Mean Slenderness ratio, λ		Mean Stress @ Yield, σ (N/mm^2)		Young's Modulus (N/mm^2)	
	Afara	Babo	Afara	Babo	Afara	Babo
200.00	13.72	13.38	16.10	31.95	930.73	1365.64
400.00	30.30	26.81	22.97	30.64	1161.30	1231.91
600.00	44.29	42.28	21.21	30.75	1016.08	978.00
800.00	58.65	53.01	19.67	30.50	853.02	1050.57
Average			19.99	30.96	990.28	1156.53

Figure 1 and 2 show the stress-slenderness ratio relationships of Afara and Babo timber specie respectively. The continuous column design equation for both timber species were equally derived using statistical regression analysis based on the results presnted on Table 3.

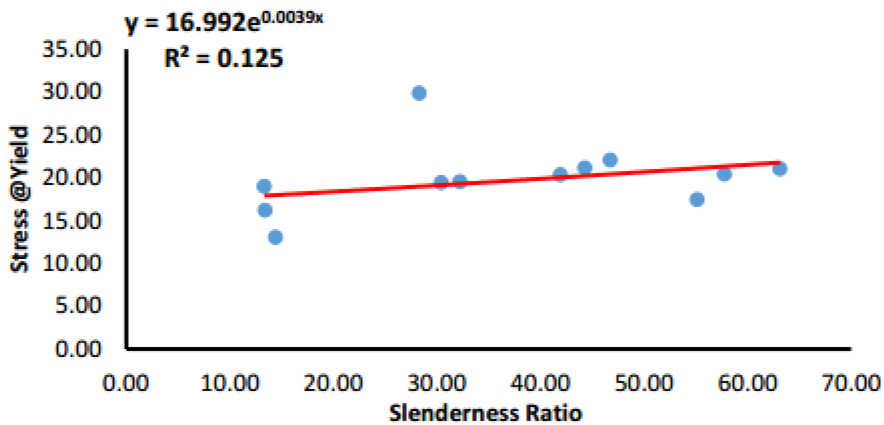

Figure 1: Stress-Slenderness ratio relationship for Afara timber specie

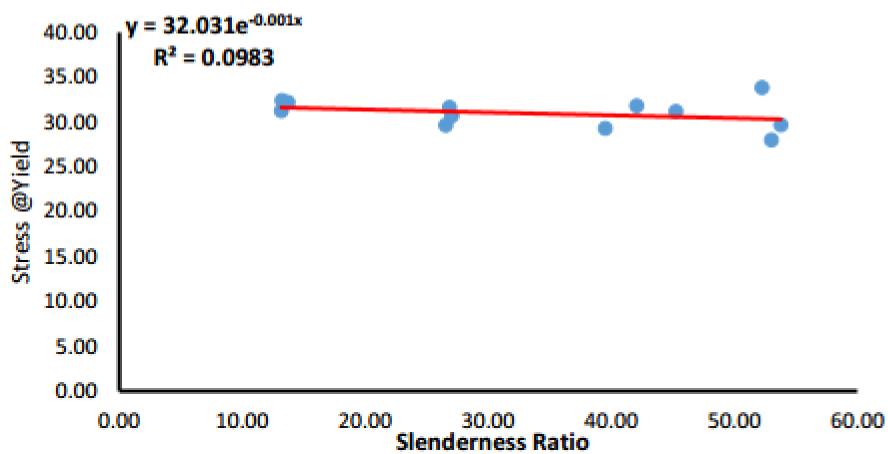

Figure 2: Stress-Slenderness ratio relationship for Babo timber specie

Verification of design equations

In other to derive a continuous column design equation for both Afara and Babo timbers, statistical regression analysis was performed on the stress at yield and slenderness ratio results for Afara and Babo timber column. The result of the regression analysis yields Equation 8 and 9 which is the desired column design equation for both Afara and Babo timbers respectively.

$$\sigma = 16.992e^{0.0039\lambda} \tag{8}$$

$$\sigma = 32.031e^{-0.001\lambda} \tag{9}$$

To examine how well the theoretical equation best fit the experimental results obtained, the values of stress at yield were obtained from the design equation with the experimental slenderness ratio as input alongside the experimental stress at yield. The ratio of the theoretical to the experimental yield stress was also calculated. It was observed that the ratio of the theoretical to experimental yield stress ranges between 77 and 121 % for Afara timber, and between 67 and 149 % for Babo timber, both having a mean value of unity. This implies that the theoretical result is in close agreement with the experimental results. Also a single factor Analysis of Variance (ANOVA) was performed on the theoretical and experimental stress at yield using the null hypothesis (H_0: μ1 = μ2) that the means are equal at 95 % confidence interval. For both timber specie, it was observed that F < Fcrit and α (0.05) < P-value. Hence, we accept the null hypothesis H_0 that the means of both the theoretical and experimental values are equal at 0.05 level of significance. This means that the theoretical stress at yield derived from the design equation agrees with the experimental results. Therefore Equation 8 and 9 can be used for the rational design of Afara and Babo timbers respectively.

Reliability Analysis

The results of the reliability analysis of Afara and Babo are presented in Table 4, 5, 6 and 7. Figure 3 and 4 show the reliability curves for Afara and Babo, respectively. The results indicate that the timber specie Afara and Babo have a reliability index of 0.63 and 0.64, respectively, (which are both greater than 0.5, the minimum index for a reliable structure according to [24], [9] and [25] for a service life of 50 years, assuming other serviceability conditions are met.

Table 4: Strength Analysis of Afara timber

Height (mm)	Average Strength (σ) (N/mm^2)	Cumulative Strength (Q_i) (N/mm^2)	Remaining Strength (R_i) (N/mm^2)	Strength Rate (d_i)
200	16.10	16.10	63.79	0.2523
400	22.97	39.07	40.82	0.3601
600	21.21	60.28	19.61	0.5196
800	19.61	79.89	0	1.0000

Average Strength rate, $d = \frac{0.2523+0.3601+0.5196+1.0000}{4} = 0.5330$

Failure rate, $\lambda = \frac{1-d}{t}$, assuming a service life of 50 years and that other serviceability conditions are met, the reliability of the Afara timber column is evaluated as shown below using Constant Failure Rate (CFR).

$$\lambda = \frac{1-0.5330}{50} = 0.00934/year$$

Table 5: Reliability of Afara using CFR

Time (years)	λt	$e^{-\lambda t}$	Time (years)	λt	$e^{-\lambda t}$
0	0	1	140	1.308	0.2704
20	0.187	0.8294	160	1.494	0.2245
40	0.374	0.6880	180	1.681	0.1862
60	0.560	0.5712	200	1.868	0.1544
80	0.747	0.4738	220	2.055	0.1281
100	0.934	0.3930	240	2.242	0.1062
120	1.121	0.3260	260	2.428	0.0882

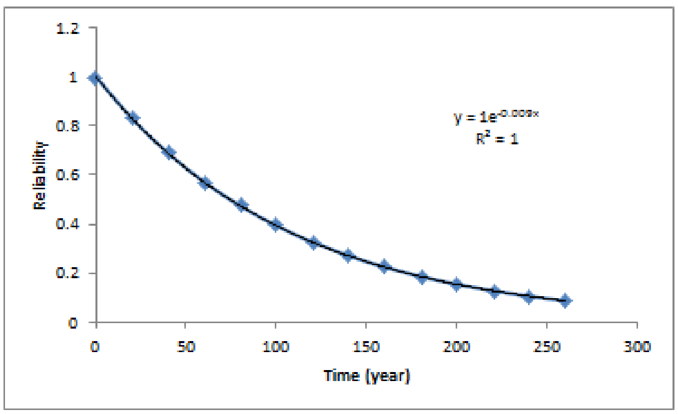

Figure 3: Reliability of Afara timber

Table 6: Strength Analysis of Babo timber

Height (mm)	Average Strength (σ) (N/mm^2)	Cumulative Strength (Q_i) (N/mm^2)	Remaining Strength (R_i) (N/mm^2)	Strength Rate (d_i)
200	31.95	31.95	91.89	0.3477
400	30.64	62.59	61.25	0.3334
600	30.75	93.34	30.50	0.5020
800	30.50	123.84	0	1.0000

Average Strength rate, $d = \frac{0.3477+0.3334+0.5020+1.0000}{4} = 0.5458$

Failure rate, $\lambda = \frac{1-d}{t}$, assuming a service life of 50 years and that other serviceability conditions are met, the reliability of the Babo timber column is evaluated as shown below using Constant Failure Rate (CFR).

$$\lambda = \frac{1-0.5458}{50} = 0.00908/year$$

Table 7: Reliability of Babo using CFR

Time (years)	λt	$e^{-\lambda t}$	Time (years)	λt	$e^{-\lambda t}$
0	0	1	140	1.271	0.2806
20	0.182	0.8336	160	1.453	0.2339
40	0.363	0.6956	180	1.634	0.1951
60	0.545	0.5798	200	1.816	0.1627
80	0.726	0.4838	220	1.998	0.1356
100	0.908	0.4033	240	2.179	0.1132
120	1.090	0.3362	260	2.361	0.0943

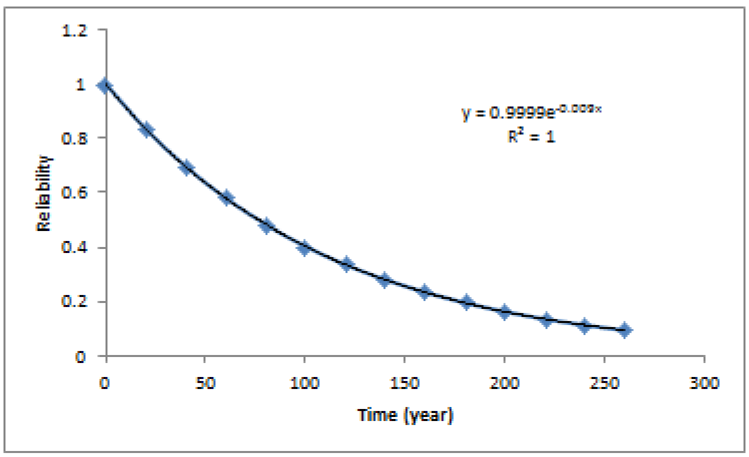

Figure 4: Reliability of Babo timber

4. Conclusion

From the study, it can be concluded that Babo has higher yield strength than Afara and thus will be more suited for Structural use. Direct relationship exists between physical properties such as moisture and density, and mechanical properties such as yield strength and modulus of elasticity. The equations derived from the regression analysis on the experimental results can be used to obtain the stress at yield if the slenderness ratio of a structural size timber column from the specie is known. With the results obtained and the associated equations derived, the strength of both timber species can be accurately predicted, thereby encouraging the use of these natural and sustainable construction materials. This design procedure is distinct and more effective than the usual procedure of classifying compression members as short, intermediate and long using their slenderness ratios according to [26]. More research work is thereby important in determining suitability of the locally available timber species. Massive afforestation practices should be encouraged and promoted in order to reduce the death of these trees and other species in the study area.

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