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Harnessing Nigeria's Forestry Potential for Structural Applications: Structural Reliability of Nigerian Grown Opepe Timber

J. I. Aguwa, S. Sadiku, M. Abdullahi

Abstract**—**This study examined the structural reliability of the Nigerian grown Opepe timber as bridge beam material. The strength of a particular specie of timber depends so much on some factors such as soil and environment in which it is grown. The steps involved are collection of the Opepe timber samples, seasoning/preparation of the test specimens, determination of the strength properties/statistical analysis, development of a computer programme in FORTRAN language and finally structural reliability analysis using FORM 5 software. The result revealed that the Nigerian grown Opepe is a reliable and durable structural bridge beam material for span of 5000mm, depth of 400mm, breadth of 250mm and end bearing length of 150mm. The probabilities of failure in bending parallel to the grain, compression perpendicular to the grain, shear parallel to the grain and deflection are 1.61×10^{-7}, 1.43×10^{-8}, 1.93×10^{-4} and 1.51×10^{-15} respectively. The paper recommends establishment of Opepe plantation in various Local Government Areas in Nigeria for structural applications such as in bridges, railway sleepers, generation of income to the nation as well as creating employment for the numerous unemployed youths.

Keywords**—**Bending and deflection, Bridge beam, Compression, Nigerian Opepe, Shear, Structural reliability.

I. Introduction

PROVISION of adequate and functional transportation infrastructure such as bridges is one of the major requirements for a comprehensive agricultural development of the nation. Many farming communities are separated from the major cities where agricultural products are sold by streams or rivers, hence facilities such as bridges to facilitate the transportation of agricultural products from the communities to the urban areas are essential. This will not only encourage the poor and despaired rural farmers but will improve the standard of living for those in urban cities by reducing the cost of foods [1]. Reinforced concrete and steel bridges are so capital intensive and as such government at various levels shy away from embanking on provision of such infrastructure thereby posing serious challenges to the poor rural dwellers who are predominantly farmers. The need for the use of locally available agricultural or forestry materials in construction industry cannot be overemphasized due to their adequacy in performance, cost effectiveness as well as generation of income and employment [2]. Engineered timber bridges that are durable, affordable and serviceable are not common in Nigeria [3].

Opepe with botanical name *Nauclea diderrichii* is a hardwood that originated from West Africa. It is known by other names in some countries as Kusia in Ghana, Badi in Ivory Coast and Bilinga in Cameroon. It is a large tree up to 50 metres in height and free from buttresses with a diameter of about 1.5 metres. Opepe has sapwood that is whitish to pale yellow in colour with orange or yellow heartwood. The grain is mostly interlocked with fairly coarse texture. Opepe is generally used for constructions, boards, beams, heavy framework, wharf and jetty decking, marine works, interior and exterior coatings as well as planks. It works moderately well with hand and machine tools and pre-boring is necessary before nailing. It can easily be glued and a high quality finish is obtainable once filled [4]. It is very durable and has a density of $740 kg/m^2$, modulus of elasticity of $13400 N/mm^2$ and belongs to strength class of D50. Opepe is famed in density and durability and is extensively used for dykes and coastal protection. It does not suffer from pin-worm hole, excessive warping or blue stain like other species. It weathers to a silver-grey colour when exposed to outdoor condition for many years and its original colour can be maintained by the use of exterior decking oil. It belongs to the family of Rubiaceae with few knots. It is highly stable, resistant to impact and negligible shrinkage It has medium bending, crushing strengths, stiffness and very high hardness [5].

The environment, the weather conditions and the soil affect the growth of trees as well as their strength properties. Most of the timber strength properties recorded in British and European codes were based on timber obtained from trees in those areas and the laboratory tests were conducted there. Since all our timber structures are constructed of timber from Nigeria, there is the great need to determine their strength properties and subject them to structural reliability analysis in order to prove their degree of structural performance [1].

Reliability is the probability of an object (item or system) performing its required function adequately for a specified period of time under stated conditions. The four essential elements of this definition are; reliability is expressed as a probability, a quality of performance is expected, it is expected for a period of time and it is expected to perform under specified conditions. Structural reliability and probabilistic methods are currently used in the development of new generation design codes, evaluation of existing structures and probability risk assessment [6]. Structural reliability

Aguwa J. I., Sadiku S. and Abdullahi M. are with the Department of Civil Engineering, Federal University of Technology, Minna, Nigeria (e-mail: james.aguwa@futminna.edu.ng).

analysis aims at producing a structure that is optimally safe, economic, functional and elegant. The question of structural reliability is more complicated for timber because of the large natural variability of the material leading to uncertainty in the design. The variability of strength between elements is significantly larger than for steel or reinforced concrete members. The coefficient of variation is of the order of 20-40%, with higher values for brittle type of failure modes [7].

One of the objectives for structural design is to fulfill certain performance criteria related to safety and serviceability. One such performance criterion is usually formulated as a limit state a mathematical description of the limit between performance and non-performance [7]. 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. The main issue is to find design methods ensuring that the relevant performance criteria are met with a certain desired level of confidence or reliability. That means that the risk of non-performance should be sufficiently low.

The beams or girders of the timber bridge deck which are major structural members in the structural system of a timber bridge are considered. When timber structural systems are made safe and reliable in road bridges, then we will not only improve the nation's economic base but also contribute immensely to the economic activities and people's well-being of the areas where they are abundantly sourced and used [8].

The usage of Nigerian timber mainly in building construction has been by intuition, guess and trial-and error due to the uncertainty about their behaviour under applied loads as a result of improper prediction of their load-carrying capacity. Timber bridge decks were common in this country in the colonial era but disappeared due to fear of high risk of failure caused by unavailable in-depth structural reliability analysis. Most Local Government Areas and individuals in the country cannot afford the high cost of reinforced concrete bridge decks. It is justifiable that with proper reliability analysis on the Nigerian timber, the life of the numerous rural dwellers will be improved tremendously as both Government and individual will likely embark on provision of low cost timber bridge decks, made of locally available and affordable structural materials. This will also create the awareness in Nigerian engineers to look inward by making use of this locally available structural material with great confidence.

According to [9], the most important processes in structural analysis are the determination of the structural behaviour based on the structural type and design variables and the sufficient examination of the effect on the whole structure. This understanding of the structural behaviour and the safety assessment can best be carried out using a reliability method. First Order Reliability Method (FORM) which uses the mean and standard deviation of the design variables was used in this research to evaluate the safety or reliability indices of the Opepe bridge beam in bending parallel to grain, shear parallel to grain and compression perpendicular to the grain. The mean and standard deviation were obtained from the test results of the strength properties of the Nigerian grown Opepe timber. First Order Reliability Method (FORM) has been used by many researchers to evaluate structural safety. For example, [10] used First Order Reliability Method (FORM) to perform a reliability-based resistance factor calibration of driven steel pipe piles and the implementation of Load and Resistance Factor Design (LRFD). Also, [11] employed the First Order Reliability Method (FORM) for the calibration of partial factors for axially loaded piles and indicated that these partial factors were dependent on resistance distribution as well as soil parameter's uncertainties. [12] used First Order Reliability Method (FORM) in conjunction with the requirement of [13] to design the components of a typical wooden floor system at different reliability levels.

The importance of this research is that actual physical and strength properties of the Nigerian timber can be used in structural design instead of using foreign values from codes that are always at variance with the locally available ones. For example, the bending stresses parallel to the grain for Ekki, Opepe and Iroko in [14] are 25.0, 17.0 and 12.6N/mm^2 respectively while 29.96, 29.53 and 18.89N/mm^2 were determined from test on the Nigerian timber, in this research.

The aim of this study is to evaluate the structural performance of the Nigerian grown Opepe timber as structural material for timber bridge beams. The specific objectives are; to determine the strength properties of the Nigerian grown Opepe timber and the structural reliability index, to establish safety standard in the use of the timber as bridge beams and to add value to our locally available and affordable structural material thereby increasing the local content of the construction industry in Nigeria, resulting in less dependence on foreign materials.

II. Material and Method

Nauclea diderrichii (Opepe) timber was bought from timber sawmill in Nigeria. Eight pieces of 50mm x 75mm x 3600mm of the Opepe samples were bought and naturally seasoned for six months for the samples to attain moisture content equilibrium environmentally. These samples were prepared and tested in accordance with British Standard [15], Methods of Testing Small Clear Specimens of Timber. Twenty (20) test specimens each were used for bending, tensile, compression, shear strengths parallel to the grain and compression perpendicular to the grain respectively, making a total of one hundred (100) test specimens. The Universal Testing Machine (UTM) used is of capacity 50kN.

A. Strength Properties

The basic bending, shear stresses parallel to the grain, compression perpendicular to the grain and modulus of elasticity for the Nigerian grown Opepe were determined using (1)-(3) respectively from [16]

B. Bending Strength Parallel to the Grain

The basic bending, and shear stresses parallel to the grain for the Nigerian Opepe timber were determined using (1):

$$f_{bpar} = \frac{f_m - 2.33\sigma}{2.25} \quad (1)$$

where $f_{b\ par}$ = basic bending stress parallel to the grain, f_m= mean value of the failure stresses, σ = standard deviation of the failure stresses.

The basic compressive stresses perpendicular to the grain for the Nigeria Opepe timber was determined using (2),

$$c_{bper} = \frac{f_m - 1.96\sigma}{1.2} \quad (2)$$

Equation (3) gives the relationship between the E_{mean} and the statistical minimum value of E appropriate to the number of species acting together,

$$E_N = E_{mean} - \frac{2.33\sigma}{\sqrt{N}} \quad (3)$$

where E_N is the statistical minimum value of E appropriate to the number of pieces N acting together (where N=1, E_N becomes the value for E_{min}) and σ is the standard deviation.

C. Structural Design of the Nigerian Opepe Timber Bridge Beam

Structural members should be so proportioned that the stresses or deformations induced by all relevant conditions of loading do not exceed the permissible stresses or deformation limits for the material or the service conditions, determined in accordance with [16]. When properly designed and protected from elements such as water, insects and fire, timber is a structurally capable, cost-effective and aesthetically pleasing material suitable in many structural applications such as in bridges [1]. However, when not properly designed or protected, timber structures are susceptible to deterioration, which can result in a decrease in structural capacity [17]. Table I shows the design information for the Nigerian grown Opepe timber bridge beam under the ultimate limit state of loading.

TABLE I
DESIGN INFORMATION REQUIRED FOR THE OPEPE TIMBER BRIDGE BEAM [18]

Width of bridge carriageway (m)	7
Number of notional lanes (No)	2
Width of notional lane (m)	3.5
HA live load per notional lane (kN/m)	30
Uniformly distributed load due to HA live load (kN/m)	8.57
Knife Edge load (KEL) per notional lane (kN)	120
Uniformly distributed load due to KEL (kN/m)	34.20

The input parameters for the structural reliability analysis of the Opepe timber bridge beam are shown in Table II. These parameters were determined from laboratory test results subjected to statistical analysis and deterministic design of the Opepe timber bridge beam.

TABLE II
INPUT PARAMETERS FOR DESIGN OF THE OPEPE TIMBER BRIDGE BEAM

Input Parameter	Value used
Breadth of beam (b) (mm)	150
Depth of beam (h) (mm)	400
Spacing of beam (Sp) (mm)	400
Plank depth (hpl) (mm)	100
Plank breadth (bpl) (mm)	250
Span of beam (L) (mm)	5000
bearing (L_b) (mm)	300
Minimum E (E_{min}) (N/mm^2)	14305
Mean E (E_{mean}) (N/mm^2)	16026
Unit weightt (Uw) kN/m^3	7.97
COV for $_{Unit\ Weight}$	6
Std. deviation (σc_{per}) (N/mm^2)	0.25
COV for comp. stress perp. ($COVc_{per}$)	2
Grade compressive stress ($c_{g\ per}$)	5.62
Mean bending Stress (f_{mpar}) (N/mm^2)	131.54
Std. deviation for bending stress (σf_{par})	12.25
COV for bending stress par. ($COVf_{par}$)	10
Grade bending stress ($f_{g\ par}$ 80%)	29.53
Std deviation for modulus of E (σ_E)	739
Beam Self Weight (SWBM)	0.48
Plank dead load (PDL) (kN/m)	0.32
Total live load on beam (TLL) (kN/m)	9.26
Mean shear stress ($v_{m\ par}$) (N/mm^2)	21.33
Std. deviation shear (σv_{par}) (N/mm^2)	3.8
COV for shear stress par. ($COVv_{par}$)	18
Grade shear stress ($v_{g\ par}$ 80%) (N/mm^2)	3.75
Mean compressive stress ($c_{m\ per}$)	10.34
COV of modulus of elasticity	5

D. Reliability Analysis for Simply Supported Opepe Timber Bridge Beam

In order to carry out structural reliability analysis of the Opepe timber bridge beam, Limit state equations were formulated under the following conditions; (1) The design bending and shear strengths parallel to the grain should not be reached or exceeded. (2) The design compressive strength perpendicular to the grain (bearing strength) should not be reached or exceeded at supports and at concentrated load points. (3) The beam's deflection should meet the serviceability deflection criteria.

E. Beam in Bending Parallel to the Grain

Considering under the Ultimate Limit State (ULS), for the moment capacity of the Opepe timber bridge beam, the performance function can be formulated for the beam bending, by considering the elastic section modulus ($Z=bh^2/6$, for a rectangular section), the applied bending moment, M and the permissible bending stress, f_b. For a beam considered to be freely hinged at its ends and carrying a uniformly distributed load of intensity W, the maximum bending moment at the mid-span of the beam due to distributed loads is, from [19],

$$M = \frac{W\ \ L^2}{8} \quad (4)$$

It is assumed that the dimensions and support conditions of the beam are adequate to prevent instability, that is deflections occur only in the loading plane. Then in accordance with strength of materials, the bending stresses in the beam are given by, from [20],

$$f_b = \frac{MY}{I} \tag{5}$$

where M is the bending moment acting on the beam as a result of external loads, I is the second moment of area of the beam cross-section, Y is the distance from the neutral axis and f_b is the bending stress at a distance Y. The maximum bending stress at the extreme fibre is given by, from [20],

$$f_b = \frac{M}{Z} \tag{6}$$

where Z is the elastic section modulus for the timber beam. Since [12] allows the design of timber structures to be carried out on the assumption that they behave elastically, the above expression may be used for the design purposes. The design bending stress parallel to the grain, f_{ppar} of the beam is defined as, from [11]

$$f_{ppar} = K_3 K_6 K_7 f_{gpar} \tag{7}$$

where f_p is the permissible bending strength, f_g is the grade bending strength from tests, given in Table V, K_3 is modification factor for duration of loading (Table 17 of [16]), K_6 is form factor [13, p.35] and K_7 is depth modification factor. The applied bending stress on the beam is

$$f_{apar} = \frac{M}{Z}. \tag{8}$$

The limit state or performance function in bending is

$$g(x) = f_{ppar} - f_{apar} \tag{9}$$

F. Beam in Shear Parallel to the Grain

It can be recalled from elastic beam theory that the formula for calculating shear stress, v at any level of a built-up section is from [16],

$$v = \frac{Va\bar{y}}{IB} \tag{10}$$

where V is the vertical external shear force, a is the area of the beam above the level at which v is being calculated, $\bar{y}$ is the distance from the neutral axis of the beam to the centre of the area a, I is the complete second moment of area of the beam at the cross-section being considered and B is the breadth of the beam at the level at which v is being calculated. For a rectangular section, the maximum horizontal shear stress occurring at the neutral axis becomes, from [16],

$$v_{apar} = \frac{3V}{2A} \tag{11}$$

where V, is the shear force, A is the total cross-sectional area of the beam.

The design shear stress parallel to the grain for the timber beam is

$$v_{ppar} = K_3 K_4 v_g \tag{12}$$

where K_4 is modification factor for bearing stress (Table 18 of [12]), v_g is the grade shear stress from Table V. The limit state or performance function in shear is

$$g(x) = v_p - v_a \tag{13}$$

G. Beam in Compression Perpendicular to the Grain

The applied compressive stress at the bearing end of the beam is given by, from [16]

$$c_{aper} = \frac{V}{b \times L_b} \tag{14}$$

where V is shear force at the bearing end, b is breadth of the beam, L_b is end bearing length

The permissible or design compressive stress perpendicular to the grain is

$$c_{pper} = K_4 K_7 c_g \tag{15}$$

where c_g is grade compressive stress perpendicular to the grain from Table V.

The limit state or performance function in compression is given by

$$g(x) = c_p - c_a \tag{16}$$

H. Beam in Deflection

Deflection in beams at a particular stage may become visually unacceptable to the occupants or leads to distortion, cracking or failure under the beam for example, violation of the serviceability limit state. In order to prevent such occurrence, deflection is limited based on past experience and observations in accordance with code recommendation. The [14] recommends 0.3% of the span or 0.003L

In timber design, a total deflection of both the bending and shear deflections are calculated or considered. In steel design, shear deflections are usually disregarded except in cases of heavily loaded and deep steel plate girders [21]. This is because timber beams are frequently deep in relation to their span and have a very low G/E value. G is the modulus of rigidity usually taken as 1/16 (0.0625) compared to 0.4 for mild steel. In deriving the limit state function for deflection, (17)-(28) from [16] were used.

The bending deflection of a timber beam in simple support is given from first principles as,

$$\Delta_b = \frac{5W_e L^3}{384EI} \tag{17}$$

The equivalent uniform load, W_e may be determined for most loading conditions as

$$W_e = WK_b \tag{18}$$

where K_b is a coefficient taken from Tables 4.9 - 4.16 of [14] according to the nature of the actual load, K_b is used for bending and K_v is used for shear. Usually the bending deflection is calculated at the mid-span and the shear deflection was determined at the same point or location. Therefore, by the method of unit load,

$$\text{Shear deflection} = F\int_0^L \frac{VV_1 dx}{AG} \quad (19)$$

where F, is a form factor dependent on the cross-sectional shape of the beam (equal to 1.2 for solid rectangle), V is the external shear due to actual loading, V_1 is the shear due to a unit load at the point where the deflection is being calculated, A is the area of the cross-section and G is the modulus of rigidity (usually taken as E/16). The shear deflection is normally added to the centre-span bending deflection; therefore, it is the centre-span shear deflection in which one is interested [16]. With the unit load placed at centre-span, V_1= 0.5 and it can be shown that

$$\text{Shear deflection at mid-span} = \frac{F \times Area of shear force diagram to mid span}{AG}$$

$$\Delta_v = \frac{FM_o}{AG} \quad (20)$$

where M_o, is the bending moment at mid-span, M_o for a simple span may be calculated as,

$$M_o = \frac{W_o L}{8} \quad (21)$$

where W_o is the equivalent uniform load to produce the moment M_o,

$$W_o = WK_v \quad (22)$$

where W = wL, is actual load and K_v is a coefficient taken from Tables 4.9-16 of [16], according to the nature of the actual load. Where more than one type of load occurs on a span, W_o is the summation of the individual WK_v values. Therefore, the deflections due to uniformly distributed load are,

$$\Delta_b = \frac{5W_e L^3}{384EI} = \frac{5W_e L^3 \times 12}{384Ebh^3} \quad (23)$$

$$\Delta_v = \frac{FM_o}{AG} = \frac{1.2 \times W_o L \times 16}{8Ebh} \quad (24)$$

Therefore, total deflection at the centre-span of the beam is

$$\text{Total deflection} = \Delta_t = \Delta_b + \Delta_v \quad (25)$$

where Δ_b = bending deflection and Δ_v = shear deflection, F = 1.2, G = E/16 and $M_o = wL^2/8$

The modulus of rigidity or bulk modulus is given as

$$G = \frac{E}{16} and AG = \frac{EBD}{16} \quad (26)$$

For the purpose of calculating deflection, the mean value of the modulus of elasticity should be used for rafters, floors, joists and other system where it can be shown that transverse distribution of load is achieved [14].

$$E_N = E_{mean} - \frac{2.33\sigma}{\sqrt{N}} \quad (27)$$

where E_N, is the statistical minimum value of the modulus of elasticity for the number of pieces acting together, E_{mean} is the mean value of modulus of elasticity and N is the number of pieces acting together at a cross-section.

In a special case when one section acts alone, N = 1 and E_N becomes the E_{min} values tabulated in [16]. By substituting the known values of E_{min}, E_{mean} and N in the formula, the value of 2.33σ can be calculated. E_{min} is used in this case and the beam is regarded as a principal member.

The limit state or performance function for deflection can be written as

$$g(x) = 0.003L - \Delta_t \quad (28)$$

The statistical parameters and their probability distribution of the basic variables used as input into the FORTRAN programme are shown in Table III.

TABLE III
PROBABILITY DISTRIBUTION AND THE STATISTICAL PARAMETERS FOR THE BASIC VARIABLES

Basic Variables	Probability Distribution	COV (%)
Uw	Lognormal	6
E	Lognormal	13
LL	Lognormal	20
L	Normal	3
b	Normal	6
h	Normal	6
f_g	Normal	9
v_g	Normal	18
c_g	Normal	11
L_b	Normal	6

I. *Method of Analysis*

The results obtained from the deterministic design of the simply supported timber bridge beam were used to carry out a reliability analysis of the beam using FORM5. FORM5 is reliability software used to estimate the probability of failure or safety index (β) of structures. The design parameters used in the analysis are shown in Table IV.

TABLE IV
DESIGN PARAMETERS FOR THE NIGERIAN GROWN OPEPE TIMBER BRIDGE BEAM

Span of beam (mm)	5000
Depth of beam (mm)	400
Breadth of beam (mm)	150
Design dead load on beam (kN/m)	0.92
Design live load on beam (kN/m)	9.26

III. Results and Discussion

A. Strength Properties of the Nigerian Opepe Timber

Table V shows the determined strength properties of the Nigerian grown Opepe timber at 18% moisture content. The Nigerian Opepe timber has basic and grade strengths that conform to [14] recommendations.

TABLE V
DETERMINED STRENGTH PROPERTIES OF THE NIGERIAN GROWN OPEPE

Type of stress	Value
Mean failure bending stress parallel to the grain (N/mm^2)	131.54
Standard deviation of failure bending stresses (N/mm^2)	12.25
Basic bending stress parallel to the grain(N/mm^2)	36.91
Grade bending stress parallel to the grain (80%) (N/mm^2)	29.53
Mean value modulus of elasticity (N/mm^2)	16026
Minimum value modulus of elasticity (N/mm^2)	14305
Density (kg/m^3)	813
Mean failure shear stress parallel to the grain (N/mm^2)	21.33
Standard deviation of failure shear stresses (N/mm^2)	3.8
Basic shear stress parallel to the grain(N/mm^2)	4.69
Grade shear stress parallel to the grain (80%) (N/mm^2)	3.75
Mean failure compressive stress across the grain (N/mm^2)	10.34
Standard deviation of failure compressive stresses across the grain (N/mm^2)	0.25
Basic compressive stress across the grain(N/mm^2)	6.32
Grade compressive stress across the grain (80%) (N/mm^2)	5.62

B. Confidence Limits for Mean and Standard Deviation

Table VI shows the confidence limits for the mean for the Nigerian grown Opepe timber and the results are satisfactory for both 95% and 99% confidence limits. The results were calculated using (29) and (30) from [20],

$$95\%\ \text{Conf. Limits} = \mu \mp t_{0.975}\frac{\sigma}{\sqrt{N-1}} \quad (29)$$

$$99\%\ \text{Conf. Limits} = \mu \mp t_{0.995}\frac{\sigma}{\sqrt{N-1}} \quad (30)$$

where μ is the mean failure bending, shear or compression stress, $t_{0.975}$ and $t_{0.995}$ are the percentile values for students distribution with v degrees of freedom, σ is the standard deviation for the failure stresses and N is the number of test specimens.

TABLE VI
CONFIDENCE LIMITS FOR THE MEAN OF THE FAILURE STRESSES FOR NIGERIAN OPEPE

Type of Stress	95% (N/mm^2)	99% (N/mm^2)	From Test (N/mm^2)
Bending along grain	127.74, 35.34	126.54, 136.54	131.54
Shear along the grain	21.15, 22.51	19.78, 22.88	21.33
Comp.perp. to grain	10.22, 10.46	10.18, 10.50	10.34

Table VII shows the confidence limits for the standard deviation for the Nigerian grown Opepe and the results are satisfactory for both 95% and 99% confidence limits. The results were calculated using (31) and (32) from [22],

$$95\% = \frac{\sigma\sqrt{N}}{\chi_{0.975}} \text{ and } \frac{\sigma\sqrt{N}}{\chi_{0.025}} \quad (31)$$

$$99\% = \frac{\sigma\sqrt{N}}{\chi_{0.995}} \text{ and } \frac{\sigma\sqrt{N}}{\chi_{0.005}} \quad (32)$$

where $\chi_{0.975}$, $\chi_{0.025}$, $\chi_{0.995}$ and $\chi_{0.005}$ are the percentile values for the Chi-Square distribution with v degrees of freedom, σ is the standard deviation for the failure bending stresses and N is the number of test specimens.

TABLE VII
CONFIDENCE LIMITS FOR THE STANDARD DEVIATION OF THE FAILURE STRESSES FOR THE NIGERIAN GROWN OPEPE

Type of Stress	95% (N/mm^2)	99% (N/mm^2)	From Test (N/mm^2)
Bending along grain	10.31, 16.34	9.75, 18.01	12.25
Shear along grain	3.3, 5.07	3.2, 5.59	3.8
Compression perp. to grain	0.20, 0.37	0.18, 0.43	0.25

Chi-Square Goodness of Fit test was carried out on the Nigerian Opepe timber using the failure bending stresses as shown in Table VIII. The normal distribution assumed for in the analysis is satisfactory.

TABLE VIII
CHI-SQUARE GOODNESS OF FIT FOR OPEPE

Class Failure Stress (N/mm^2)	Class bound	Prob. for each class	Exp. freq.	Obs. freq.
	79.5			
80 – 89	89.5	0	0	1
90 – 99	99.5	0.002	0.08	0
100 – 109	109.5	0.016	0.64	1
110 – 119	119.5	0.038	1.52	1
120 – 129	129.5	0.199	7.96	2
130 – 139	139.5	0.311	12.44	23
140 – 149	149.5	0.253	10.12	8
150 – 159	159.5	0.119	4.76	4
160 – 169	169.5	0.032	1.28	0
			38.8	40

$$\chi^2 = \sum (Oi - Ei)2 / Ei = 7.73$$

For v = l-1-k = 9-1-2 = 6

For v = 6, $\chi^2_{0.950} = 12.60$

The fit of the data is very good for normal distribution assumed since 12.60 > 7.73

C. Stress-Strain Relation for the Nigerian Opepe Timber

Fig. 1 shows the stress-strain relationship for the Nigerian Opepe timber in bending parallel to the grain. Limit of proportionality is exhibited, thereby confirming that the Nigerian Opepe timber is an elastic structural material.

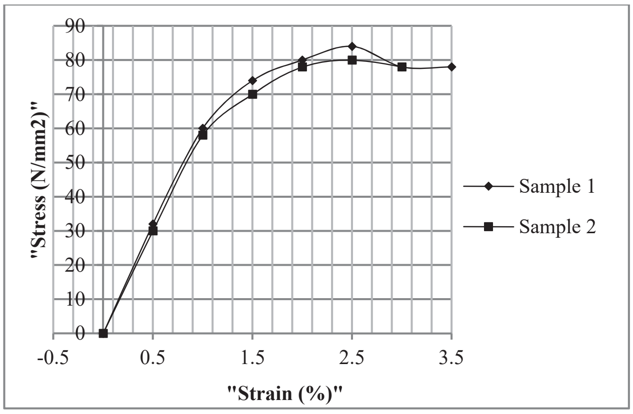

Fig. 1 Stress-Strain relation for the Nigerian grown Opepe timber in bending

D. Reliability Assessment

The results of the reliability assessment of the Nigerian grown Opepe timber bridge beam are shown in Table IX. The reliability analysis was carried out on the Nigerian Opepe timber bridge beam at the Ultimate Limit State of loading subjected to bending, shear, compression and deflection forces. Using 2.5 as the target reliability index, the Nigerian grown Opepe is safe as timber bridge beam subjected to these forces, under the specified design conditions of loading and geometrical properties. This result agrees with [23] who stated that target reliability index (β) for timber ranges from 2.0 to 3.0 with strong mean of 2.5. The degree of reliability can further be improved if suitable cross-section is chosen by reducing the span and increasing the depth of the beam. This also conforms to the report by [24] that the safety of the timber column can be enhanced if adequate and suitable dimensions are chosen to have a lower slenderness ratio.

TABLE IX
RELIABILITY INDEX FOR THE NIGERIAN GROWN OPEPE TIMBER BRIDGE BEAM

Beam in bending parallel to the grain (β)	5.11
Beam in shear parallel to the grain (β)	3.35
Beam in compression perpendicular to the grain (β)	5.53
Beam in deflection (β)	7.89

E. Probability of Failure (P_f)

Failure occurs when the demand exceeds the capacity. Mathematically denoted as, $g < 0$. From [24],

$$P_f = P(g < 0) = \Phi(-\beta) \quad (33)$$

where Φ is the standard normal distribution function (zero mean and unit variance)

Using (33), the probabilities of failure of the Nigerian grown Opepe timber bridge beam in bending, shear parallel to grain, compression perpendicular to the grain and deflection are 1.61×10^{-7}, 1.93×10^{-4}, 1.43×10^{-8} and 1.51×10^{-15} respectively.

F. Sensitivity Analysis

In order to examine the effect of the depth of beam, live load on beam, breadth of beam, unit weight of Opepe, span of beam and end bearing length of beam, on the reliability index, sensitivity analysis was performed by varying each of them.

Fig. 2 shows the relationship between reliability index (β) and depth (h) for the Nigerian grown Opepe timber bridge beam subjected to bending, shear, compression and deflection forces. As the depth of beam was increased from 300 to 500mm, the reliability index, (β) increased. The increase in reliability index (β) could be attributed to the increase in the rigidity of the beam. At the ultimate limit state of loading, depth of 400mm, span of 5000mm and with a target reliability of 2.5, the Nigerian Opepe timber is safe as a structural bridge beam material. It was reported by [1] that at large depth, the structure may be reliable but not economical because drying and lifting will be a problem. [25] stated that since structural safety must recognize financial burden involved in project execution and general utility, the derived factors of safety are improved to balance conflicting aims of safety and economy.

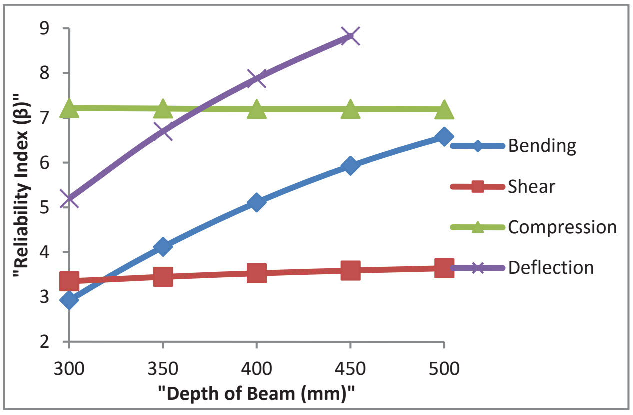

Fig. 2 Reliability Index - Depth relation for the Nigerian Opepe bridge beam.

Fig. 3 shows the relationship between reliability index and live load for a simply supported Nigerian grown Opepe timber bridge beam subjected to bending, shear, compression and deflection forces at the ultimate limit state of loading with variable live load. The reliability index (β) was decreasing as the live load was increased from 5kN/m to 20kN/m. This could be as a result of loading beyond the carrying capacity of the structural beam thereby leading to the chances of failure. A maximum of 10kN/m live load can adequately be sustained by the Nigerian Opepe as bridge beam at a span of 5000mm, depth of 400mm, breadth of 150mm under the Ultimate Limit State of loading.

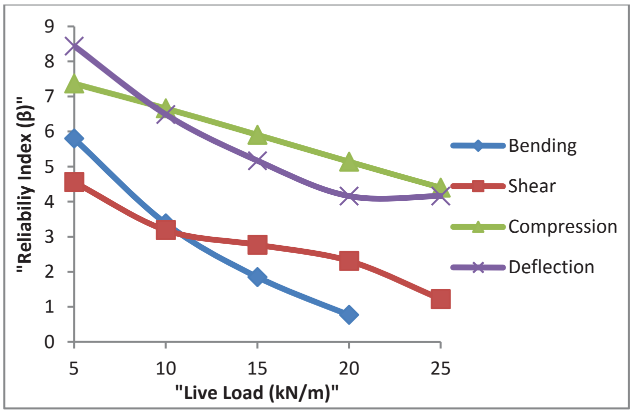

Fig. 3 Reliability Index - Live Load relation for the Nigerian Opepe timber bridge beam

In Fig. 4, significant increase in reliability index (β) was observed as the breadth was increased from 150mm to 350mm for the Nigerian grown Opepe timber bridge beam subjected to bending, compression and deflection forces but remained near constant when subjected to shearing forces. This could be attributed to the slight increase in EI values, which increased the rigidity of the beam. The Nigerian Opepe timber bridge beam is reliable at a minimum breadth of 150mm under the specified design conditions.

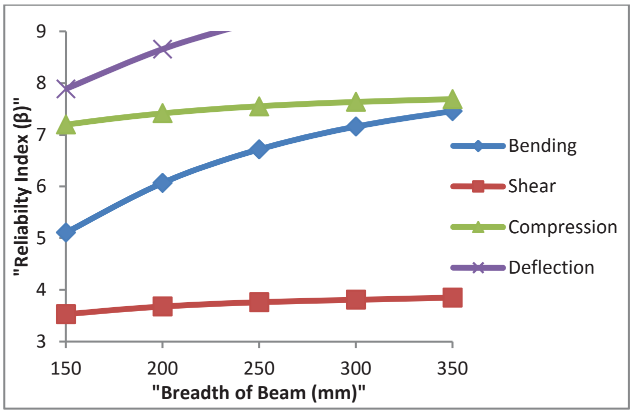

Fig. 4 Reliability Index - Breadth relation for the Nigerian Opepe timber bridge beam

The effect of varying the unit weight of the Nigerian grown Opepe timber bridge beam on the reliability index is shown in Fig. 5 and slight decrease in reliability index (β) was noted as the unit weight increased from $10kN/m^3$ to $30kN/m^3$. This trend could be attributed to the fact that unit weight increases dead load which in turn reduces the reliability index. However, the effect of unit weight on the reliability index is not significant and this conforms to the report by [26].

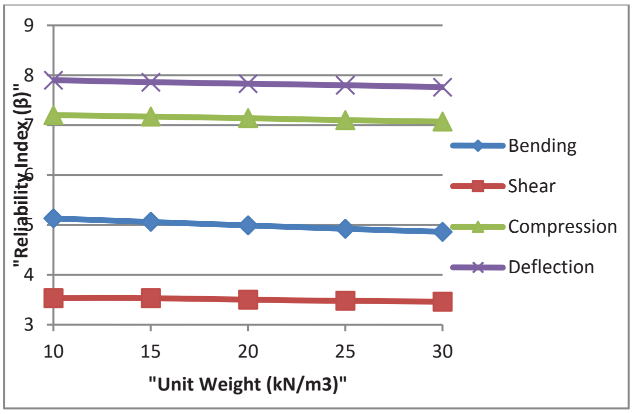

Fig. 5 Reliability Index – Unit weight relation for the Nigerian Opepe bridge beam

Fig. 6 shows the relationship between reliability index and span for simply supported Nigerian grown Opepe timber bridge beam subjected to bending, shear, compression and deflection forces under the Ultimate Limit State of loading and at variable span. Sharp decrease in reliability index was observed as the span was increased from 5000mm to 10000mm. The Nigerian grown Opepe timber bridge beam is safe as a structural bridge beam material for span not exceeding 6000mm.

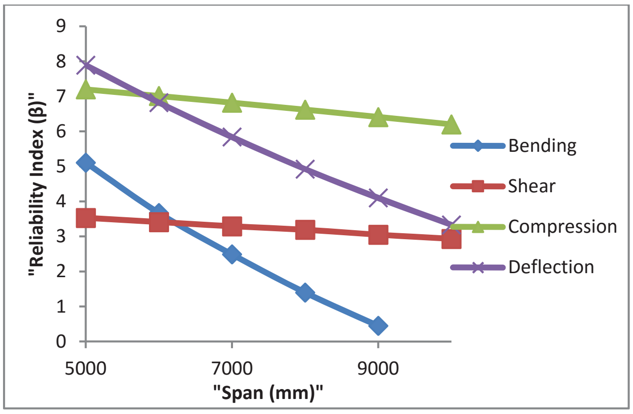

Fig. 6 Reliability Index - Span relation for the Nigerian grown Opepe timber bridge beam

Fig. 7 shows the relationship between reliability index and end bearing length for a simply supported Nigerian grown Opepe timber bridge beam subjected to bending, shear, compression and deflection forces. It was found that the Nigerian Opepe timber bridge beam is reliable even at a minimum end bearing length of 100mm under the designed conditions.

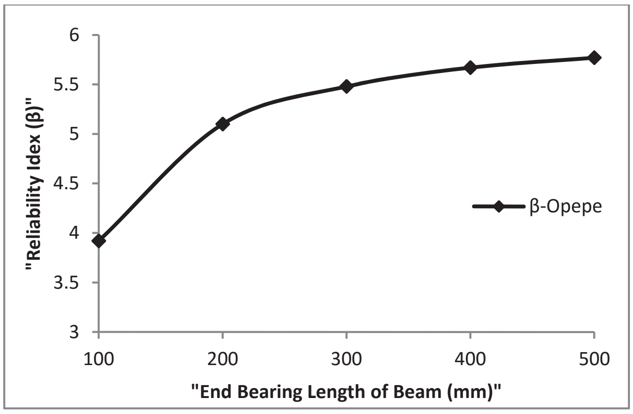

Fig. 7 Reliability Index - End bearing length relation for the Nigerian grown Opepe bridge beam

IV. Conclusion

The Nigerian grown Opepe timber is a reliable structural material for timber bridge beams for spans not exceeding 6000mm, depth of 400mm, breadth of 150mm and minimum end bearing length of 100mm. The strength properties of the Nigerian grown Opepe timber are in good conformity with BS 5268 recommendations. The safety index of the Nigerian grown Opepe timber bridge beam is highly sensitive to the depth and the span of the beam; hence they are the critical factors to be considered in the structural analysis and design of timber bridge beams. The reliability index of the Nigerian grown Opepe timber bridge beam is highly sensitive to bending forces; hence these forces should always be investigated to establish the degree of reliability.

V. Recommendation

The researchers recommend that Opepe timber bridges should be encouraged in Nigeria so as to link most of the rural dwellers to the urban areas where their agricultural products can be sold. With such low cost bridges access roads will be provided and the cost of transportation will highly be reduced leading again to cheap foods in the urban cities. In order to create more employment opportunities, Opepe plantation should be established in each Local Government Area in Nigeria. This will ensure availability of the structural material as well as steady jobs for those who will be involved in maintaining the plantations, felling down the trees, transporting them, conversion, seasoning and construction activities. This recommendation if carried out will drastically increase the local content in the construction industries, hence creating positive impact on the overall economy of Nigeria.

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