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Reliability Assessment of the Nigerian Apa (Afzelia Bipindensis) Timber Bridge Beam Subjected to Bending and Deflection Under the Ultimate Limit State of Loading

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ABSTRACT

Structural reliability analysis was carried out on the Nigerian grown Apa (Afzelia bipindensis) timber, to ascertain its structural performance as timber bridge beams. Two pieces of 50mm x 75mm x 3600mm of Nigerian grown Apa hardwood were bought, seasoned naturally and 80 pieces of test specimens were prepared for determination of their strength properties, (which include bending and tensile strengths parallel to grain) at a moisture content of 18%, in accordance with the British Standard BS 373 of 1957. Statistical analysis was carried out using the strength properties for determination of mean, standard deviation, coefficient of variations, confidence limits and Chi-Square goodness of fits. Structural analysis and design of a timber bridge beam using the determined data from the Nigerian Apa timber, in accordance with BS 5268 were carried out under the Ultimate Limit State of loading. Programme development for reliability assessment was written in FORTRAN programming language. Reliability analysis was carried out to ascertain its level of safety using First-Order Reliability Method (FORM). Sensitivity analysis was also carried out by varying the depth of beam, imposed live load, breadth of the beam, unit weight of the Apa timber, span of the beam as well as the end bearing length. The result revealed that the Nigerian grown Apa timber is a satisfactory structural material for timber bridge beams at depth of 400mm, breadth of 150mm and span of 5000mm under the ULSL. The probabilities of failure of the Nigerian Apa timber bridge beam in bending and deflection are 2.062×10^{-3} *and* 2.673×10^{-14} respectively, under the design conditions.

Keywords: *Nigerian Apa, Safety index, Strength, Structural reliability analysis, Timber bridge beam,*

NOMENCLATURE

A	Total cross-sectional area of the beam
b	Breadth of beam
bpl	Breadth of plank deck
$COVf_{par}$	Coefficient of variation for bending stress parallel to grain
COV_{Uw}	Coefficient of variation for unit weight of the Nigerian grown Iroko
E	Modulus of elasticity for the Nigerian grown Apa
E_{mean}	Statistical mean value of modulus of elasticity
E_{min}	Minimum value of modulus of elasticity
E_N	Statistical minimum value of E appropriate to the number of pieces N acting together
F	Form factor dependent on the cross-sectional shape of the beam
$f_{a\ par}$	Applied bending stress on the beam parallel to grain
$f_{b\ par}$	Basic bending stress parallel to the grain for the Nigerian grown Apa
$f_{g\ par}$	Grade bending stress parallel to the grain for the Nigerian grown Apa
$f_{m\ par}$	Mean failure stress parallel to the grain for the Nigerian grown Apa
$f_{p\ par}$	Permissible bending stress parallel to the grain for the Nigerian grown Apa
G	Modulus of rigidity
g(x)	Limit state or performance function
h	Depth of the Apa timber bridge beam
hpl	Thickness of the Apa bridge plank deck
I	Second moment of area of the Apa bridge beam cross-section
K_3	Modification factor for duration of loading
K_4	Modification factor for bearing stress
K_6	Form factor

K_7	Depth modification factor
K_b	Coefficient dependent on nature of actual bending load
K_v	Coefficient dependent on nature of actual shearing load
L	Span of the Nigerian grown Apa timber bridge beam
L_b	End bearing length of the Nigerian grown Apa timber bridge beam
LL	Live load on the Nigerian grown Apa timber bridge beam
M	Bending moment on the Apa bridge beam
M_o	Bending moment at mi-span of the Nigerian grown Apa bridge beam
PDL	Nigerian grown Apa bridge plank dead load
Sp	Spacing of the Nigerian grown Apa timber bridge beam
SWBM	Self weight of the Nigerian grown Apa bridge beam
$t_{b\ par}$	Basic tensile stress parallel to the grain for the Nigerian grown Apa
TLL	Total live load on the Nigerian grown Apa bridge beam
Uw	Unit weight of the Nigerian grown Apa
V	Shear force
V_1	Shear due to unit load at the point where deflection is being calculated
w	Uniformly distributed load on the timber beam
σ	Standard deviation

1. INTRODUCTION

Construction activities using vast quantities of locally available raw materials are major steps towards industrialization and economic independence for developing countries that are emphasizing more interest in timber. Structural timber is the timber used in framing and load-bearing structures, where strength is the major factor in its selection and use. Most woods used in the building construction are softwoods but in structures like bridges and railway sleepers, hardwoods are specially used (Karlsen and Slitskouhov, 1989). According to NCP 2: 1973, Apa (Afzelia) is a very durable hardwood, has excellent resistanance to attack by termites and available commonly in savana and high forests. Refers to as African wood, it is found in tropical Africa or Asia with origin from Cameroon. The timber remains smooth under friction and it shows only small movement with time. Apa timber has good machining qualities, it sands to a smooth surface and its uses include flooring, furniture, decking, stair rails and construction.

This study brings to focus current reasoning and the integration of advanced technologies to suit the available climatic, natural and human resources to solve the problem of transportation, by making cheaper, better and more reliable structural system in highways (Aguwa, 2011). 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 peoples well-being of the areas where they are abundantly sourced and used Abejide, O.S. (2007).

According to Nowak, 2004, structural reliability and probabilistic methods have continued to develop a growing importance in modern structural engineering practice especially when it involves naturally occuring materials such as timber. They are currently used in the development of new generation design codes, evaluation of existing structures and probability risk assessment. The primary goal of engineered construction is to produce a structure that optimally combines safety, economy, function and aesthetics. Afolayan and Adeyeye, 1998, reported that wood, like other building materials, has inherent advantages that make it especially attractive in specific applications.

According to Thelandersson, 2003, 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 that is a mathematical description of the limit between performance and non-performance. 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 question of reliability is especially complicated for timber because of the large natural variability of the material. A significant element of uncertainty is also introduced through lack of information about the actual physical variability. Thelandersson, 2003, stated that the variability of strength between elements is significantly larger than for steel or reinforced concrete members.

The aim of this study is to evaluate the conformity of Nigerian grown Apa timber to the current BS 5268 (2002) specifications for timber bridge decks. The strength of timber depends so much on the nature of the soil and the entire environment in which the tree is grown. The specific objectives are; to conduct experiments on the Nigerian Apa timber with a view to establishing their strength properties, to utilize the strength properties of the Nigerian Apa timber so obtained to determine its conformity to the International Standard, to determine the structural reliability index for the Nigerian Apa timber, to establish safety standard in the use of the Nigerian Apa timber as a bridge structural material 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.

2. MATERIALS AND METHODS

Apa; The Nigerian grown Apa timber sawn to size 50mm x 75mm x 3600mm were bought from timber market at Sapele, Nigeria.

2.1 Preparation and Testing of the samples

Two pieces of 50mm x 75mm x 3600mm of the Nigerian grown Apa timber bought from timber market were taken to African Timber and Plywood Sapele where they were naturally seasoned for eight months in order to attain moisture content equilibrium environmentally. Forty test specimens of the Nigerian grown Apa timber were prepared for each of the following tests; bending strength parallel to the grain and tensile strength parallel to the grain. A total of 80 test specimens of the Nigerian Apa timber were prepared and tested in accordance with BS 373 of 1957, Methods of Testing Small Clear Specimens of Timber. The whole preparation of the test specimens of timber was carried out at African Timber and Plywood (AT & P) Sapele while the actual testing using Universal Testing Machine (UTM) of capacity 50kN was performed at National Centre for Agricultural Mechanization (NCAM) in Ilorin Kwara State, Nigeria.

2.2 Bending Strength Parallel to the Grain

The basic bending stress parallel to the grain for the Nigerian Apa timber was determined using the failure stresses from tests. From (Ozelton and Baird, 1981)

$$f_{b\ par} = \frac{f_m - 2.33\sigma}{2.25} \qquad (1)$$

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

Tensile Strength Parallel to the Grain

The basic tensile stress parallel to the grain for the Nigerian Apa timber was determined using the failure stresses from tests. From (Ozelton and Baird, 1981)

$$t_{b\ par} = \frac{f_m - 2.33\sigma}{2.25}. \qquad (2)$$

2.3 Modulus of Elasticity

The formula below gives the relationship between the E_{mean} and the statistical minimum value of E appropriate to the number of species acting together, From (Ozelton and Baird, 1981),

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

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.

3. DESIGN OF THE NIGERIAN APA 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 BS 5268-2. 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. However, when not properly designed or protected, timber structures are susceptible to deterioration, which can result in a decrease in structural capacity.

Table 1: Design information for the Nigerian grown Apa timber bridge

Width of bridge carriageway	7 m
Number of notional lanes	2
Width of notional lane	3.5 m
HA live load for a notional lane (BS 5400)	30 kN/m
Uniformly distributed load due to HA live load	8.57 kN/m
Knife Edge load (KEL) per notional lane (BS 5400)	120 kN
Uniformly distributed load due to KEL	34.20 kN/m

Source: BS 5400; Part 2; 1978: Specification for loads

Total uniformly distributed load on the Apa timber bridge beam

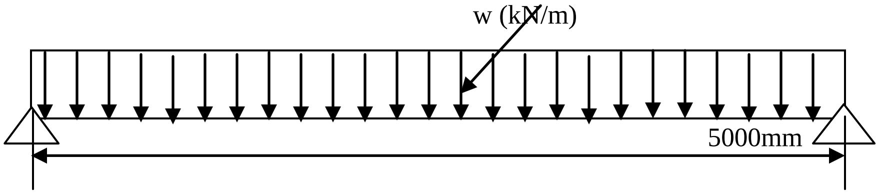

Fig. 1A: Loading on Simply Suported Nigerian grown Apa timber bridge beam

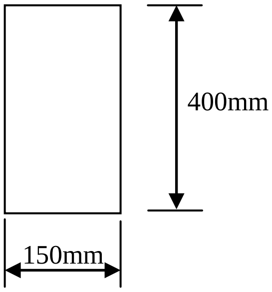

Fig.1B: Cross-Section of the Nigerian grown Apa timber bridge beam

Table 2: Input parameters for the design of the Nigerian Apa timber bridge beam in bending and deflection

Input Parameter	Value used	Input Parameter	Value used
Unit weightt (UW)	7.98	Breadth of beam (b)	150
COV_{UW}	11	Mean bending stress ($f_{m\ par}$)	121.44
Depth of beam (h)	400	Std. deviation (σf_{par})	16.3
Spacing of beam (SP)	400	Coefficient of variation ($COVf_{par}$)	13
Plank depth (hpl)	100	Grade bending stress ($f_{g\ par}$ 80%)	23.94
Plank breadth (bpl)	250	Span of beam (L)	5000
End bearing (L_b)	300	Minimum E (E_{min})	9024
Mean E (E_{mean})	12429	Std deviation (σE)	1461
Beam Self wt (SWBM)	0.48	Plank dead load (PDL)	0.32
Total live load (TLL)	6.17		

Source: Determined from tests and Deterministic design of the Nigerian Apa bridge beam

3.1 Reliability Analysis for Simply Supported Nigerian Apa Timber Bridge Beam

The design procedure for timber beams subjected to bending and deflection, where the direction of the grain in the wood is parallel to the span is to ensure that;

a. The design bending strength parallel to the grain is not reached or exceeded and the bending stresses do not cause lateral torsional buckling of the beam leading to a premature instability failure.

b. The beam's deflection meets the serviceability deflection criteria.

3.2 Beam in Bending Parallel to the Grain

Considering under the Ultimate Limit State (ULS), for the moment capacity of the 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 (Singh S, 1981)

$$M = \frac{WL^2}{8} \tag{7}$$

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 (Nash, 1977),

$$f_b = \frac{MY}{I} \tag{8}$$

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 from (8) is from (Nash, 1977),

$$f_b = \frac{M}{Z} \tag{9}$$

where Z is the elastic modulus for the timber. Since BS 5268 (2002) 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, $f_{p\ par}$ of the beam is defined as

$$f_{p\ par} = K_3 K_6 K_7 f_{g\ par} \tag{10}$$

where $f_{p\ par}$ = the permissible bending strength, $f_{g\ par}$ = the grade bending strength from tests, given in Table 2, K_3 = modification factor for duration of loading (Table 17 of BS 5268), K_6 = form factor (Page 35 of BS 5268), K_7 = depth modification factor. The applied bending stress parallel to the grain on the beam is given by

$$f_{a\ par} = \frac{M}{Z}. \tag{11}$$

The limit state or performance function in bending is given by

$$g(x) = f_{p\ par} - f_{a\ par} \tag{12}$$

3.3 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 BS 5268 (2002) 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 (Owens and Davison, 2005). 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.

The bending deflection of a timber beam in simple support is given from first principles as, from (Ozelton and Baird, 1981),

$$\Delta_b = \frac{5W_eL^3}{384EI} \quad . \tag{13}$$

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

$$W_e = WK_b \tag{14}$$

where K_b is a coefficient taken from tables 4.9 - 16 (Ozelton and Baird, 1981) 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, from (Ozelton and Baird, 1981),

$$\text{Shear deflection} = F\int_0^L \frac{VV_1dx}{AG} \tag{15}$$

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 (Ozelton and Baird, 1981). With the unit load placed at centre-span, V_1= 0.5 and it can be shown that

Shear deflection at mid-span= $\frac{F \times Area\ of\ shear\ force\ diagram\ to\ midspan}{AG}$, from (Ozelton and Baird, 1981),

$$\Delta_v = \frac{FM_o}{AG} \tag{16}$$

where M_o, is the bending moment at mid-span, M_o for a simple span may be calculated as, From (Ozelton and Baird, 1981),

$$M_o = \frac{W_oL}{8} \tag{17}$$

where W_o is the equivalent uniform load to produce the moment M_o. From (Ozelton and Baird, 1981),

$$W_o = WK_v \tag{18}$$

where W = wL, is actual load and K_v is a coefficient taken from Tabes 4.9-16 (Ozelton and Baird, 1981), 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. The deflections due to uniformly distributed load are, from (Ozelton and Baird, 1981),

$$\Delta_b = \frac{5W_eL^3}{384EI} = \frac{5W_eL^3\times 12}{384Ebh^3} \qquad (19)$$

and from (Ozelton and Baird, 1981),

$$\Delta_v = \frac{FM_o}{AG} = \frac{1.2\times W_oL\times 16}{8Ebh} \qquad (20)$$

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

$$\text{Total deflection} = \Delta_t = \Delta_b + \Delta_v \qquad (21)$$

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

$$G = \frac{E}{16} \text{ and } AG = \frac{EBD}{16} \qquad (22)$$

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 (BS 5268, 2002), from (Ozelton and Baird, 1981),

$$E_N = E_{mean} - \frac{2.33\sigma}{\sqrt{N}} \qquad (23)$$

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 (BS 5268, 2002). 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

$$g(x) = 0.003L - \Delta_t \qquad (24)$$

The statistical parameters and their probability distribution of the basic variables used as input into the FORTRAN programme are shown in table 3 below.

Table 3: Probability distribution and the statistical parameters for the basic variables

Basic Variables	Probability Distribution	Coefficient of variation	Basic Variables	Probability Distribution	Coefficient of variation
Uw	Lognormal	11	h	Normal	6
E	Lognormal	12	f_g	Normal	13
LL	Lognormal	20	L	Normal	3
b	Normal	6	L_b	Normal	6

Source: From test results on the Nigerian grown Apa timber analyzed statistically

3.4 Method of Analysis

Programme development for reliability assessment was written in FORTRAN programming language described by Lipshutz and Poe (1978). 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 4

Table 4: Design parameters for the Nigerian Apa timber bridge beam

Specie	Span mm	Depth mm	Breadth mm	Design dead load kN/m	Design live load kN/m
Apa	5000	400	150	0.92	9.26

Source: Deterministic design of the Nigerian grown Apa timber bridge beam

4. RESULTS AND DISCUSSION

4.1 Structural/ Strength Properties of the Nigerian Apa Timber

Tables 5 - 6 show the determined strength properties of the Nigerian Apa timber at 18% moisture content and the basic and grade strengths conform to International Standards (BS 5268 codes of practice).

Table 5: Strength/Physical properties of Nigerian timber at moisture content of 18%

Mean value modulus of elasticity, E_{mean} (N/mm^2)	12429
Minimum value modulus of elasticity, E_{min} (N/mm^2)	9024
Density (kg/m^3)	84
Basic bending stress parallel to the grain ((N/mm^2)	29.92
Basic tensile stress parallel to the grain (N/mm^2)	28.85

Source: From tests on the Nigerian grown Apa timber

Table 6: Mean failure Stresses, Standard deviation, Basic stresses and Grade Stresses for Nigeria grown Apa timber

Type of Stress	Mean failure stress	Standard deviation	Basic stress	Grade Sresses			
				80	63	50	40
	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2
Bending stress parallel to grain	121.44	16.30	29.92	23.94	18.85	14.96	11.97
Tensile stress Parallel to grain	109.99	12.66	28.85	23.08	18.18	14.43	11.54

Source: From tests on the Nigerian grown Apa timber

4.2 Confidence Limits for Mean and Standard Deviation

Table 7 and 8 show the confidence limits for the mean and standard deviation respectively for the Nigerian Apa and the results are satisfactory for both 95% and 99% confidence limits.

Table 7: Confidence Limits for the mean of the failure bending stress

Specie	95% Confidence Limits (N/mm^2)	99% Confidence Limits (N/mm^2)	Mean from Tests (N/mm^2)
Apa	115.70 and 125.50	114.15 and 127.05	121.44

Source: From tests on the Nigerian grown Apa timber and subjected to statistical analysis

Table 8: Confidence Limits for the standard deviation of the failure bending stress

Specie	95% Confidence Limits (N/mm^2)	99% Confidence Limits (N/mm^2)	Standard deviation from Tests (N/mm^2)
Apa	13.32 and 21.11	12.59 and 23.27	16.30

Source: From tests on the Nigerian grown Apa and subjected to statistical analysis

4.3 Chi-Square Goodness of Fit

Table 9 shows the Chi-Square Goodness of Fit for Nigerian Apa timber and the result is satisfactory confirming that the normal distribution assumed is a good fit.

Table 9: Chi-Square Goodness of Fit for the Nigerian Apa timber

Class Failure Stress (N/mm^2)	Class boundaries	Probability for each class	Expected frequency	Observed frequency
	79.5			
80 – 84	84.5	0.01	0.27	1
85 – 89	89.5	0.01	0.38	1
90 – 94	95.5	0.03	1.02	1
95 – 99	99.5	0.04	1.71	2
100 – 104	104.5	0.06	2.47	2
105 – 109	109.5	0.09	3.52	4
110 – 114	114.5	0.11	4.25	1
115 – 119	119.5	0.12	4.96	2
120 – 124	124.5	0.13	5.07	8
125 – 129	129.5	0.11	4.54	6
130 – 134	134.5	0.10	3.93	4
135 – 139	139.5	0.08	3.12	6
140 – 144	144.5	0.06	2.22	1
145 – 149	49.5	0.03	1.28	1
			38.74	40

Source: From tests on the Nigerian grown Apa timber and subjected to statistical analysis

(From Spigel, 1972), $\chi^2 = \sum (Oi - Ei)2/Ei = 13.0$
For v = L-1-k = 14-1-2 = 11
For v = 11, $\chi^2_{0.950} = 19.7$

The fit of the data is very good for normal distribution assumed since 19.7 > 13.0. This result is in good agreement with that reported by Aguwa and Sadiku, 2011 for the Nigerian Ekki timber.

4.4 Stress-Strain Relation for the Nigerian Apa Timber

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

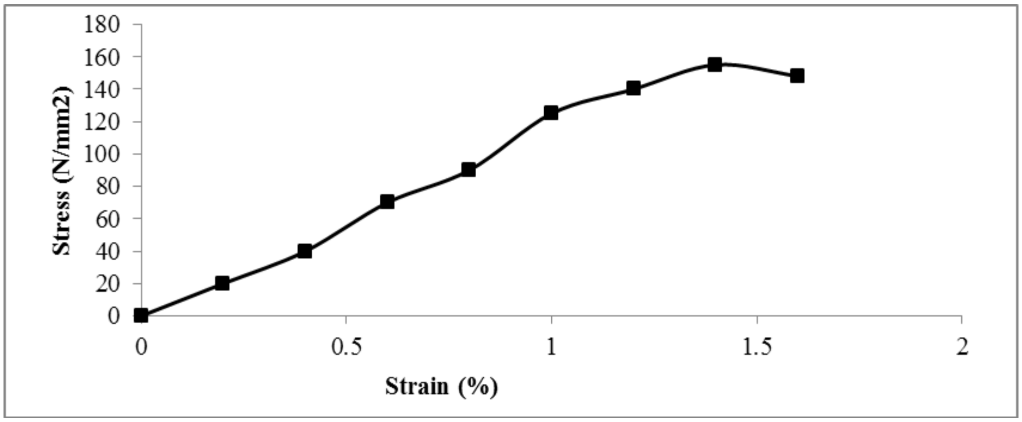

Fig. 1: Stress-Strain relation for the Nigerian Apa timber

4.5 Load-Deflection Relation for the Nigerian Apa Timber

The relationship between load and deflection for Nigerian Apa timber in bending parallel to the grain is shown in Fig.2. A coresponding increase in deflection with increase in applied load was observed and it can be seen that timber does not move into plastic stage of deformation.

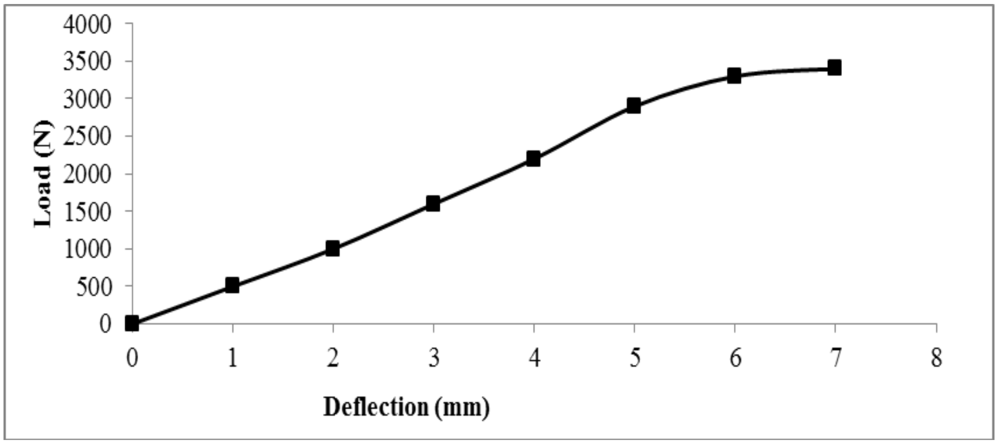

Fig. 2: Load-Deflection relation for the Nigerian Apa timber

4.6 Reliability Assessment

The results of the reliability assessment of the Nigerian Apa timber bridge beam subjected to bending and deflection forces are shown in Table 10. The reliability analysis was carried out on the Nigerian Apa timber bridge beam at the ultimate limit state of loading subjected to bending and deflection forces. Using 2.5 as the target reliability index, the Nigerian Apa is safe as timber bridge beam subjected to bending and deflection, under the specified design conditions of loading and geometrical properties. This result conforms to that reported by Aguwa and Sadiku, 2011 for the Nigerian Ekki timber. This is in accordance with Melchers (1987) who stated that target reliability (β) for timber members ranges from 2.0 to 3.0 with strong mean of 2.5.

Table 10: Safety Indices for the Nigerian Apa timber bridge beam in bending and deflection under the ultimate limit state of loading

Beam in bending parallel to the grain (β)	4.11
Beam in deflection (β)	8.05

4.7 Probability of Failure (P_f)

Failure occurs when the demand exceeds the capacity. Mathematically denoted as $g < 0$, from (Melchers, 1987), Probability of failure,

$$P(failure), P_f = P(g < 0) = \Phi(-\beta) \qquad (25)$$

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

The probabilities of failure of the Nigerian Apa timber bridge beam in bending and deflection are 2.062×10^{-3} and 2.673×10^{-14} respectively.

4.8 Sensitivity Analysis

Fig. 3 shows the relationship between safety index (β) and depth (h) for the Nigerian Apa timber bridge beam subjected to bending and deflection forces. A general increase in safety index (β) was noted as the depth was increased from 300 to 500mm. This increase in safety index (β) could be attributed to the increase in EI values which increased the rigidity of the beam. At the ultimate limit state of loading and at a depth of 400mm and span of 5000mm, the Nigerian Apa timber is safe in bending and deflection. It is to be noted that at large depth, the structure may be reliable but not economical because drying and lifting will be a problem (Aguwa 2010). 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 (Afolayan, 1995)

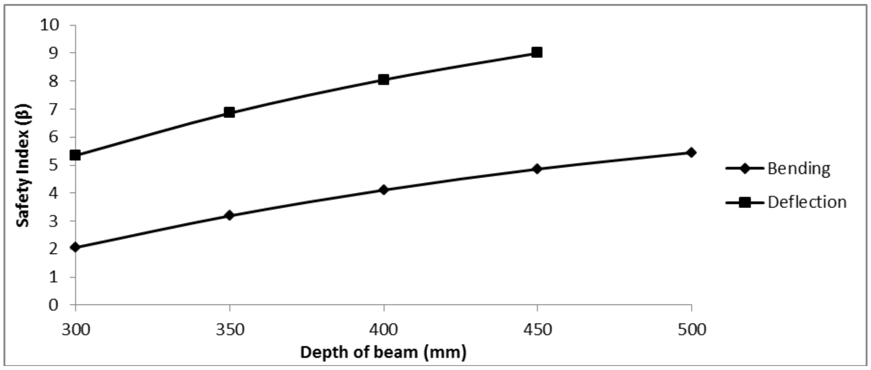

Figure 3: Safety Index - Depth relation for the Nigerian Apa timber bridge beam

Fig. 4 shows the relationship between safety index and live load for a simply supported Nigerian grown Apa timber bridge beam subjected to bending and deflection forces at the ultimate limit state of loading and at variable live load. A decrease in safety index (β) was recorded as the live load was increased from 5kN/m to 20kN/m. This could be attributed to the fact that the carrying capacity of the structural element is being exceeded thereby leading to the chances of failure. A maximum of 10kN/m live load can adequately be sustained by the Nigerian Apa at a span of 5000mm, depth of 400mm and breadth of 150mm. This result is similar to that reported by Aguwa and Sadiku, 2011 on the Nigerian grown Ekki timber subjected to bending forces.

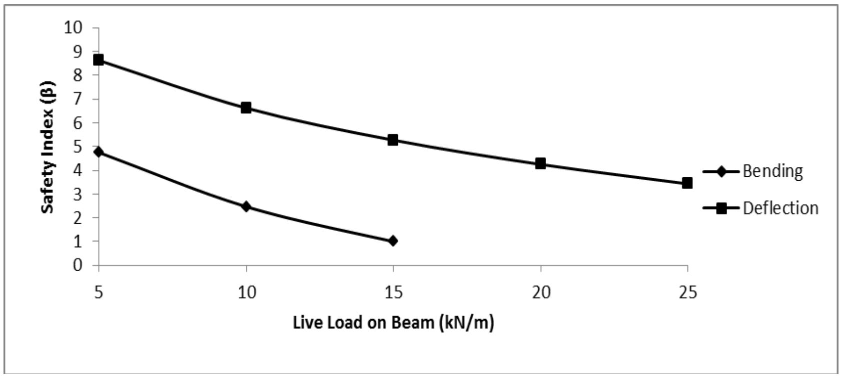

Fig. 4: Safety Index - Live Load relation for the Nigerian Apa timber bridge beam

In Fig. 5, a general consistent increase in safety index (β) was observed as the breadth was increased from 150mm to 350mm for the Nigerian Apa timber bridge beam subjected to bending and deflection forces. This could be attributed to the increase in EI values, which increased the rigidity of the beam. The Nigerian Apa timber bridge beam is safe at a minimum breadth of 150mm under the specified design conditions and this is in conformity to report by Aguwa, 2011.

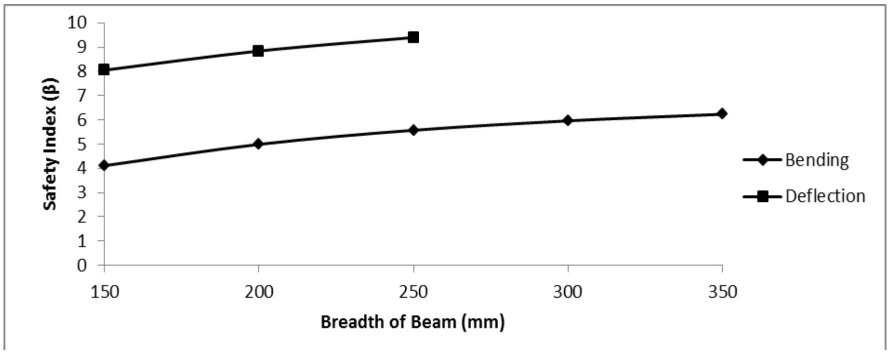

Fig. 5: Safety Index - Breadth relation for the Nigerian Apa timber bridge beam

The effect of varying the unit weight of the Nigerian Apa timber bridge beam subjected to bending and deflection on the safety index is shown in Fig. 6 and slight decrease in safety 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 dead load increases with increase in unit weight and this will definitely reduce the safety index. However, the effect of unit weight on the reliability index is not significant and this conforms to the report by Nowak and Eamon (2008).

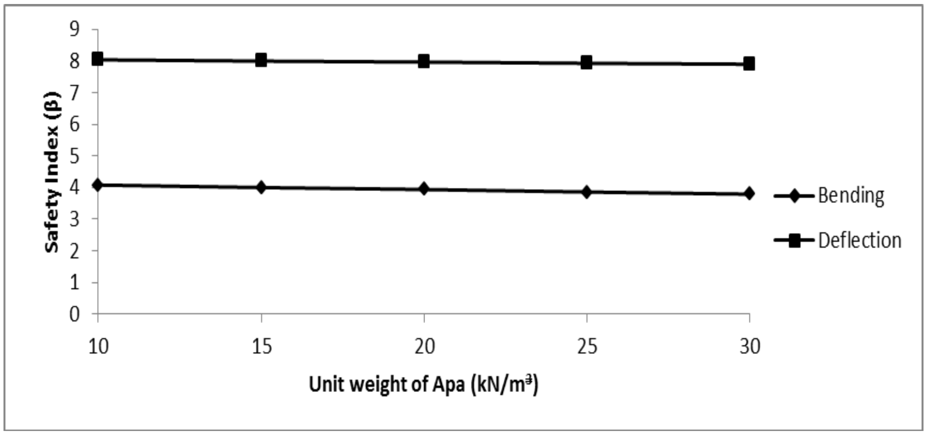

Fig. 6: Safety Index – Unit Weight relation for the Nigerian Apa timber bridge beam

Fig. 7: shows a simply supported Nigerian Apa timber bridge beam subjected to bending and deflection forces under the ultimate limit state of loading and at variable span. Sharp decrease in safety index was noted as the span was increased from 5000mm to 10000mm. According to Aguwa, 2010 increasing the span implies an increase in bending moment which is a major factor that causes failure of beam. The Nigerian Apa timber bridge beam is safe in bending and deflection for span of up to 6000mm. The effect of span on the safety index of the Nigerian Apa timber bridge beam is more significant in bending parallel to the grain than in deflection.

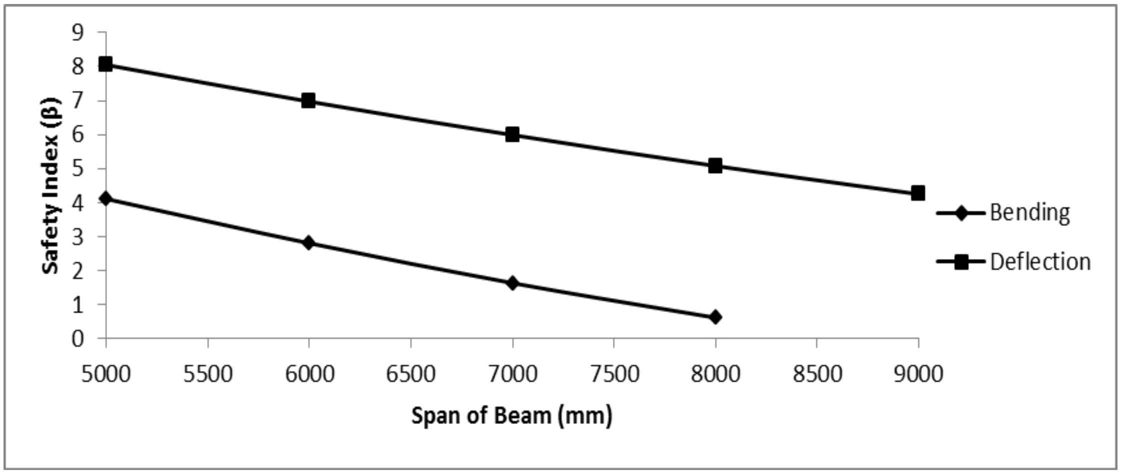

Fig. 7: Safety Index - Span relation for the Nigerian Apa bridge beam in bending and deflection.

Fig. 8: shows the relationship between safety index and end bearing length and it was found that the Nigerian grown Apa timber is reliable even at a minimum end bearing length of 100mm.

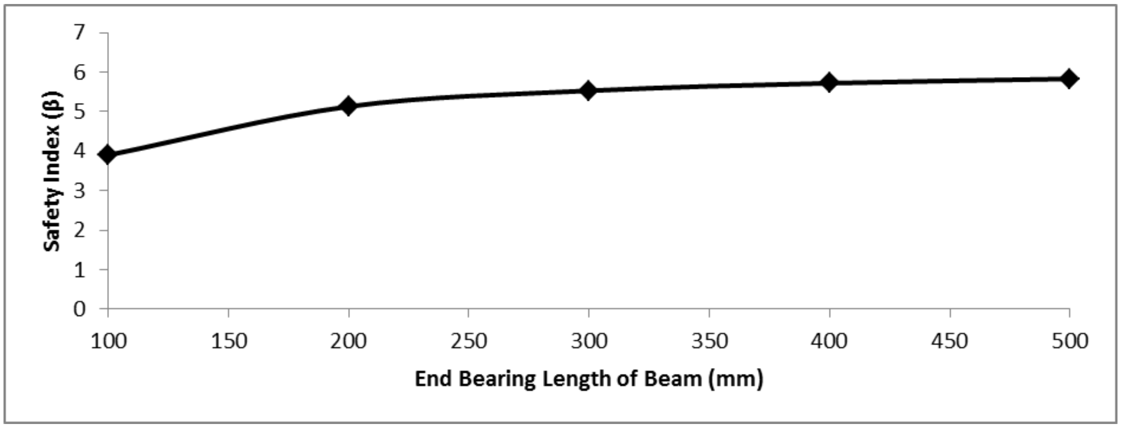

Fig. 8: Safety Index - End Bearing Length relation for the Nigerian Apa bridge beam

5. CONCLUSION

The overall conclusions emerging from this study are;

a. The Nigerian grown Apa timber is a reliable structural material for timber bridge beams for spans not exceeding 6000mm, depth of 400mm and breadth of 150mm.

b. The structural/strength properties of the Nigerian grown Apa timber are in good conformity to the International Standards (BS 5268)
c. The safety index of the Nigerian Apa 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 design of timber bridge beams.

d. The reliability index of the Nigerian Apa timber bridge beam is highly sensitive to bending forces; hence these forces should always be investigated to establish the degree of reliability.

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