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Full Length Research Paper

Reliability studies on the Nigerian Ekki timber as bridge beam in bending under the ultimate limit state of loading

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This paper provides the results of structural reliability analysis carried out on the Nigerian Ekki timber subjected to bending forces, to ascertain its structural performance as a timber bridge beam. Samples of the Nigerian Ekki timber were collected, seasoned naturally and their structural/strength properties were determined at a moisture content of 18%, in accordance with the British Standard BS 373, methods of testing small clear specimens of timber. Statistical analysis was carried out using the structural/strength properties determined. Structural analysis and design of a timber bridge beam using the Nigerian Ekki timber in accordance with BS 5268 were carried out under the ultimate limit state of loading. Reliability analysis of the Ekki timber bridge beam so designed to ascertain its level of safety was carried out using first-order reliability method (FORM). Sensitivity analysis was carried out by varying the depth of beam, imposed live load, breadth of the beam, unit weight of the timber, span of the beam as well as the end bearing length. The result revealed that the Nigerian Ekki timber is a satisfactory structural material for timber bridge beams at depth of 400 mm, breadth of 150 mm and span of 5000 to 7000 mm under the ultimate limit state of loading. Its probability of failure in bending under the specified operating conditions is 1.1 x 10^{-7}, that is, one in ten million.

Key words: Bridge beam, Nigerian Ekki, reliability, safety, strength, structural material, timber, ultimate limit state.

INTRODUCTION

The need for local content in construction of engineering infrastructure is now a serious engineering challenge in Nigeria. This is because vast quantities of local raw materials, which must be processed and used for cost effective construction abound. Construction activities based on these locally available raw materials are major steps towards industrialization and economic independence for developing countries. This explains huge interest and considerable intellectual resources being invested in understanding the mechanical or structural properties of the Nigerian timber. Vander and Cowan (1995) concluded that a good environment that is full of vitality is bound to increase people's sense of well being.

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

Structural timber is the timber used in framing and load-bearing structures, where strength is the major factor in its selection and use. Trees are the only sources of

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timber, and those that carry naked seeds are called softwoods, while those with seeds inside a fruit are termed hardwoods and Ekki is one of them. 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).

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 (Thelandersson, 2003). 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. 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 to 40%, with higher values for brittle type of failure modes (Thelandersson, 2003).

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. 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 (2007).

The aim of this study is to evaluate the conformity of Nigerian Ekki timber to the current BS 5268 (2002) specifications for timber bridge decks. The specific objectives are; (i) to conduct experiments on the Nigerian Ekki timber with a view to establishing their structural/ strength properties. (ii) to utilize the strength properties of the Nigerian Ekki timber so obtained to determine its conformity to the International Standard (iii) to determine the structural reliability index for the Nigerian Ekki timber. (iv) to establish safety standard in the use of the Nigerian Ekki timber as a bridge structural material and (v) 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.

MATERIALS AND METHODS

Ekki

Nigerian Ekki timber was collected from AT & P Sapele, Nigeria.

Preparation and testing of the samples

The Nigerian Ekki samples after collection were naturally seasoned for eight months for the samples to attain moisture content equilibrium environmentally. The natural seasoning was preferred to the artificial seasoning which is faster because the proposed timber structure is bridge, which is always completely exposed to natural atmospheric weather conditions. The timber samples were prepared and tested in accordance with the British Standard BS 373 (1957), Methods of Testing Small Clear Specimens of Timber.

Bending strength parallel to the grain

The basic bending stress parallel to the grain for the Nigeria Ekki timber was determined using the failure stresses from tests by (Ozelton and Baird, 1981)

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

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

Modulus of elasticity

Equation 2 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)

$$E_N = E_{mean} - \frac{2.33\sigma}{\sqrt{N}} \quad (2)$$

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.

Structural analysis and design of Nigerian Ekki 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 shows the design information while Table 2 shows the input parameters for the reliability analysis of the Nigerian Ekki timber bridge beam.

Table 1. Design information for the timber bridge.

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

Table 2. Input parameters for the design of the Nigerian Ekki timber bridge beam.

Input Parameter	Value used	Input Parameter	Value used
Unit weight of Ekki (kN/m^3)	11.33	Breadth of beam (mm)	150
COV of Unit weight of Ekki	6	Failure stress of Ekki (N/mm^2)	138.32
Depth of Ekki bridge beam (mm)	400	Std dev. of failure stress(N/mm^2)	14.52
Spacing of beam (mm)	400	COV of stress for Ekki	13
Depth of plank deck (mm)	100	Grade stress (80%) (N/mm^2)	29.96
Breadth of plank deck (mm)	250	Plank deck dead load (kN/m)	0.45
Span of beam (mm)	5000	Minimum E, E_{min} (N/mm^2)	13990
End bearing length of beam (mm)	300	Std dev. of E, σ_E (N/mm^2)	1350
Mean E, E_{mean} (N/mm^2)	17135	Self weight of beam ((kN/m)	0.68
Total live load (kN/m)	6.17		

Reliability analysis for simply supported Nigerian Ekki timber bridge beam

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

1. The design bending strength parallel to the grain is not reached or exceeded.
2. The bending stresses do not cause lateral torsional buckling of the beam leading to a premature instability failure. This analysis was carried out with respect to the Ultimate Limit State of loading.

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, 1981).

$$M = \frac{WL^2}{8} \quad (3)$$

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 (Nash, 1977)

$$f_b = \frac{My}{I} \quad (4)$$

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 (Nash, 1977)

$$f_b = \frac{M}{Z} \quad (5)$$

Where; Z is the section 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 Equation 5 may be used for the design purposes. The design bending stress parallel to the grain, $f_{p\ par}$ of the beam is defined as (BS 5268, 2002).

$$f_{p\ par} = K_3 K_6 K_7 f_{g\ par} \quad (6)$$

where; f_p = the permissible bending strength, f_g = the grade bending strength from tests, given in Table 6, 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 on the beam is given by (Nash, 1977)

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

Basic variables	Probability distribution	Coefficient of variation
Uwt (Unit weight)	Lognormal	6
E (Modulus of elasticity)	Lognormal	8
LL (Live load)	Lognormal	20
L (Span)	Normal	3
b (Breadth)	Normal	6
H (Depth)	Normal	6
f_g (Grade stress)	Normal	11
L_b (End bearing length)	Normal	6

Table 4. Design parameters for the Nigerian Ekki timber bridge beam.

Species	Span (mm)	Depth (mm)	Breadth (mm)	Design dead load (kN/m)	Design live load (kN/m)
Ekki	5000	400	150	1.3	9.26

Table 5. Stresses and Standard deviation for the Nigerian Ekki Timber.

Type of stress	Mean failure stress (N/mm^2)	Standard deviation (N/mm^2)	Basic stress (N/mm^2)	Grade stresses			
				80 (N/mm^2)	63 (N/mm^2)	50 (N/mm^2)	40 (N/mm^2)
Bending stress parallel to the grain	138.32	14.52	37.45	29.96	23.59	18.73	14.98

$$f_{a\,par} = \frac{M}{Z}. \quad (7)$$

The limit state or performance function in bending is given by (Nowak and Collins, 2000)

$$g(x) = f_{p\,par} - f_{a\,par} \quad (8)$$

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. Table 3 shows the probability distribution and the statistical parameters for the basic variables used in the reliability analysis while Table 4 shows the design parameters for the Nigerian Ekki timber bridge beam.

RESULTS AND DISCUSSION

Structural/Strength properties of the Nigerian timber

Table 5 shows the determined structural/strength properties of the Nigerian Ekki timber, at 18% moisture content. The Nigerian Ekki timber has basic and grade strengths that conform to International Standards and are slightly higher than those recorded in BS 5268 codes of practice. For example, the grade bending stress and shear stress parallel to grain for Ekki in BS 5268 are 25.0 and 3.0 N/mm^2 while that of Nigerian specie determined from test are 29.96 and 3.84 N/mm^2 respectively. The mean and minimum values moduli of elasticity of the Nigerian Ekki are 17135 and 13990 N/mm^2 respectively while the density is 1156 kg/m^3.

Confidence limits for mean and standard deviation

Tables 6 and 7 show the confidence limits for the mean and standard deviation respectively for the Nigerian Ekki and the results are satisfactory for both 95 and 99% confidence limits.

The Chi-Square Goodness of Fit for the Nigerian Ekki timber

The normal distribution assumed in the reliability analysis was confirmed by the application of chi-square goodness of fit. From (Spiegel, 1972)

Table 6. Confidence Limits for the mean for the Nigerian Ekki in Bending.

Species	95% Confidence limits (N/mm^2)	99% Confidence limits (N/mm^2)	Mean from tests (N/mm^2)
Ekki	134.60 and 143.32	133.22 and 144.70	138.96

Table 7. Confidence Limits for the standard deviation for the Nigerian Ekki in Bending.

Species	95% Confidence limits (N/mm^2)	99% Confidence limits (N/mm^2)	Standard deviation from tests (N/mm^2)
Ekki	11.85 and 1878	11.20 and 20.70	14.07

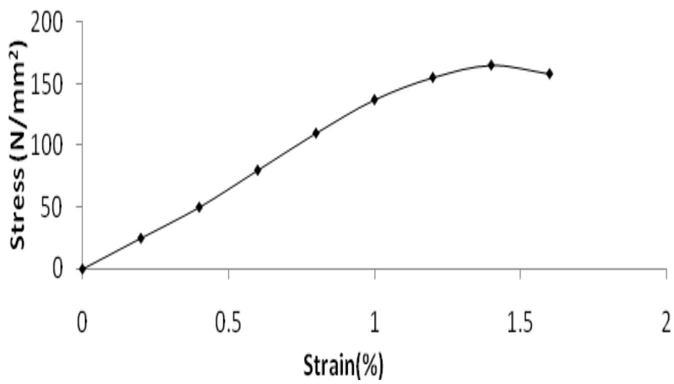

Figure 1. Stress-Strain Relation for the Nigerian Ekki timber in bending parallel to the grain.

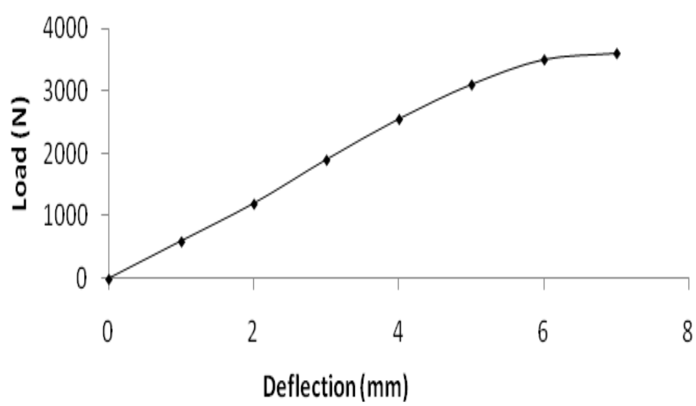

Figure 2. Load-Deflection Relation for the Nigerian Ekki in bending parallel to the grain.

$\chi^2 = \sum (Oi - Ei)2 / Ei$ = 6.56, for v = L-1-k = 9-1-2 = 6, for v = 6, $\chi^2_{0.950}$ = 12.60

where; O_i is the observed frquency and E_i is the expected frequency. The result of the Chi-Square Goodness of Fit for the Nigerian Ekki timber is satisfactory confirming that the normal distribution assumed is a good fit, since 12.60 > 6.56.

Stress-strain relation for the Nigerian Ekki timber in bending

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

The relationship between load and deflection for the Nigerian Ekki timber in bending parallel to the grain is shown in Figure 2. A corresponding 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.

Reliability assessment

The reliability analysis was carried out on the Nigerian Ekki timber bridge beam at the ultimate limit state of loading subjected to different types of forces. Using 2.5 as the target reliability index, the Nigerian Ekki is safe as timber bridge beam subjected to bending, under the specified design conditions of loading and geometrical properties, with a reliability index of 5.18

Sensitivity analysis

Figure 3 shows the relationship between safety index (β) and depth of the Nigerian Ekki timber bridge beam in bending parallel to the grain. A general increase in safety index (β) was noted as the depth was increased from 300 to 500 mm. 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 minimum depth of 300 mm and span of 5000mm, the Nigerian Ekki timber with a safety index of 2.97 is reliable for the beam bending parallel to the grain. 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. 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).

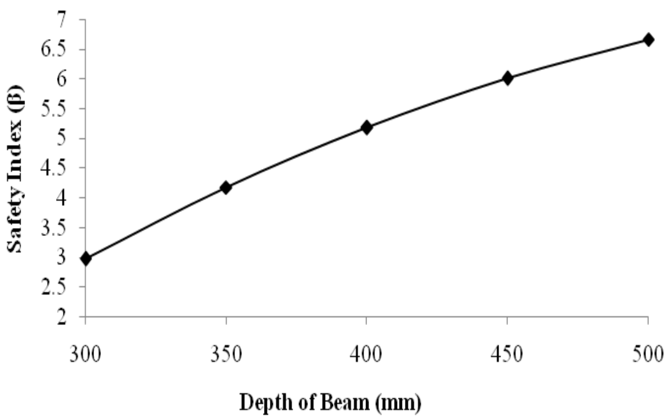

Figure 3. Safety Index - Depth Relation for the Nigerian Ekki bridge beam in bending parallel to the grain.

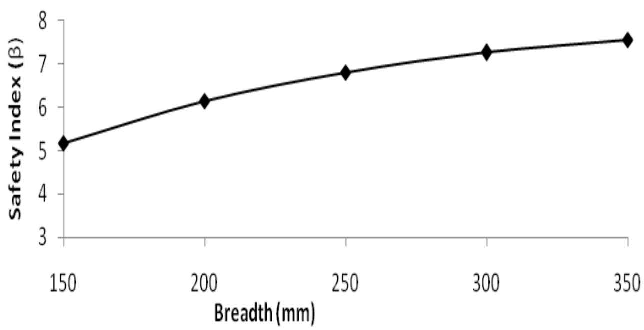

Figure 5. Safety Index - Breadth Relation for the Nigerian Ekki bridge beam in bending parallel to the grain.

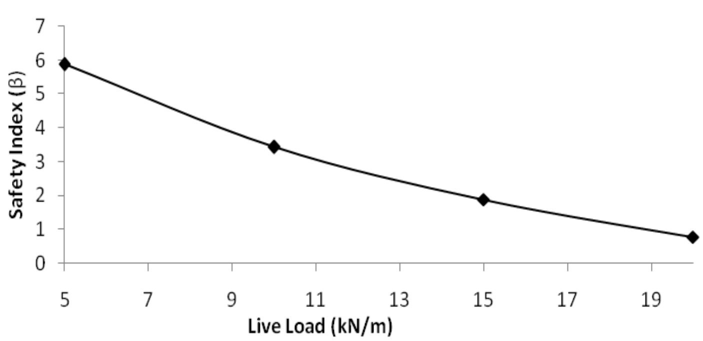

Figure 4. Safety Index - Live Load Relation for the Nigerian Ekki bridge beam in bending parallel to the grain.

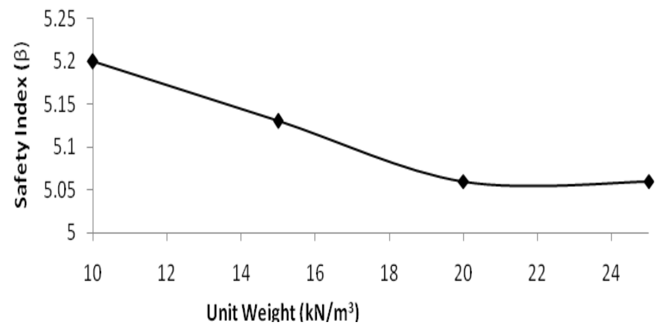

Figure 6. Safety Index – Unit Weight Relation for the Nigerian Ekki bridge beam in bending parallel to the grain.

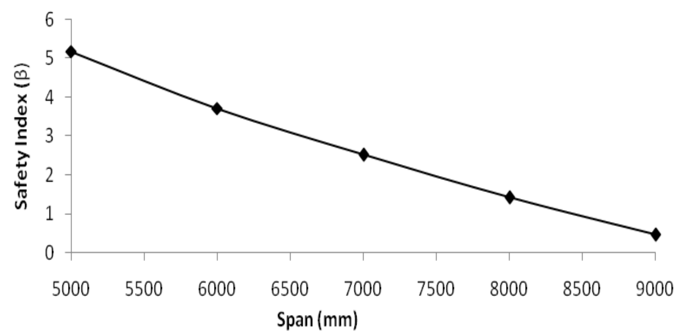

Figure 7. Safety Index - Span Relation for the Nigerian Ekki bridge beam in bending parallel to the grain.

Figure 4 shows a simply supported Nigerian Ekki timber bridge beam subjected to bending parallel to the grain 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 5 to 20 kN/m. This could be attributed to the fact that the carrying capacity of the structural element was being exceeded thereby leading to the chances of failure. A maximum of 10 kN/m live load was adequately sustained by the Nigerian Ekki in bending at a span of 5000 mm, depth of 400 mm and breadth of 150 mm.

In Figure 5, a general consistent increase in safety index (β) was observed as the breadth was increased from 150 to 350 mm for the Nigerian Ekki timber bridge beam subjected to bending parallel to the grain at the Ultimate Limit State of loading. This could be attributed to the increase in EI values, which increased the rigidity of the beam. In bending parallel to the grain, the Nigerian Ekki was safe at a minimum breadth of 150 mm under the specified design conditions.

The effect of varying the unit weight on the safety index is shown in Figure 6. There was slight decrease in safety index (β) as the unit weight increased from 10 to 20 kN/m^3. This trend could be attributed to the fact that dead load increases with increase in unit weight and as noted before, increase in load will definitely reduce the safety index. However, the effect of unit weight on the reliability index was not significant and this conforms to the report by Nowak and Eamon (2008).

Figure 7 shows a simply supported Ekki timber bridge beam subjected to bending parallel to the grain at variable span. Sharp decrease in safety index was noted as the span was increased from 5000 to 10000 mm. This

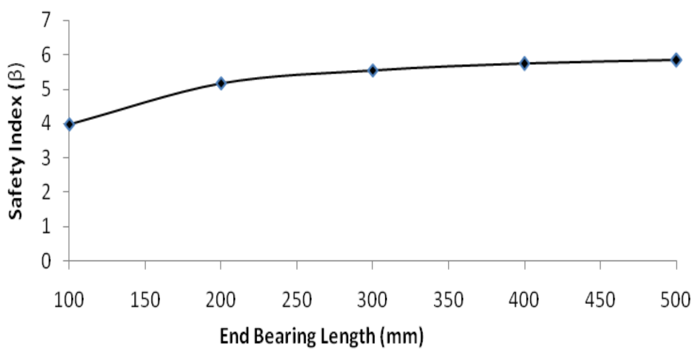

Figure 8. Safety Index - End Bearing Length Relation for the Nigerian Ekki bridge beam in bending parallel to the grain.

is because increasing the span implies an increase in bending moment which is a major factor that causes bending of beam. The Nigerian Ekki timber bridge beam with reliability index of 3.72 is safe for span of up to 6000 mm in bending parallel to the grain (Aguwa, 2010). The effect of span on the safety index is more significant in bending parallel to the grain than in shear parallel to the grain, compression perpendicular to the grain and deflection.

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

Conclusions

The overall conclusions emerging from this study are;

1. The Nigerian Ekki timber is a reliable structural material for timber bridges.
2. The structural/strength properties of the Nigerian Ekki timber are good on the scale of international standards (BS 5268).
3. The safety index of the Nigerian Ekki timber 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.

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