A DEVELOPMENT OF MATERIAL SAFETY COEFFICIENTS FOR SOLID TIMBER IN NIGERIA BASED ON EUROCODE

By

Abubakar Idris and Mohammed Jibrin Kaura
Department of Civil Engineering
Ahmadu Bello University, Zaria
Corresponding E-mail: idrcivil1@yahoo.com

ABSTRACT

The Nigerian code of practice for the design of timber structures NCP2 [1] based on the permissible stress design method with reference to British standards CP112 [2], which had passed through several revisions since 1967, up to B5268 [3], now replaced with the Eurocode 5 [4]. There is therefore the need to revise the Nigerian Timber design standard based on the current International trend. Currently, many developing countries like South Africa, Malaysia and Singapore are adopting and domesticating the Eurocode. In order for Nigeria not to be left out of the current global trend for its quest to be among the first twenty great economies by the year 2020, development of local limit state design code for timber structures in Nigeria through the adoption of the Eurocode 5 was proposed in this paper. Local material safety coefficients based on the extensive data on the material properties of Nigerian solid timber made available by the research unit of Cirad [5] were calibrated. The calibration was undertaken based on reliability principles in order to fully accommodate uncertainties that are inherent in the properties of timber. Code calibration software developed by the Joint Committee on Structural Safety (JCSS) was adopted.

Keywords: Nigerian timber; Material safety coefficients; Design code; Reliability; Eurocode 5

INTRODUCTION

Design of timber structures in Nigeria had been based on the NCP2 [1] and is largely based on British Standard, CP112 [2], which was revised to BS5268 [3]. These timber design codes were based on the permissible stress design philosophy. The complete adoption of the Eurocode 5 (EC5) in March, 2010 is a particularly significant milestone, representing a major departure from the permissible stress approach, which has endured in BS5268 [3]. EC5 is based on limit state safety format that follows a substantially different philosophy to the former codes in some important respects. First, EC5 relied upon relatively succinct principle clauses, often stated in the form of algebraic or symbolical expressions. These principles and expressions are then backed by application rules which are also quite terse. Secondly, limit state method is very different from the permissible stress method, in that it attempts to address separately various concepts of failure through rules based on reliability theory. EC5, requires the grading of timber species according to the International Strength Class System; EN 338 [6]. In the grading process, the mean Modulus of Elasticity (MOE), the characteristic values of bending strength and density are required [7, 8]. These are known as the reference material properties, which are determined in the laboratory, and the other characteristic strength and stiffness properties, such as bending and compressive strength parallel and perpendicular to grain are calculated from those basic ones [8, 9, 10, 11, 12, 13].

The large variability in the mechanical properties of solid timber requires the adoption of probabilistic approach to design of timber structures. This can be achieved by considering the EC5 provision within reliability based design framework. Information on the variability in timber properties is therefore required. The data on the variability in the properties of a considerable number of Nigerian timber species was made available through separate recent research work [5]. This information was used in this study to generate new material safety coefficient based on reliability principles as recommended in Eurocode0 [14].

A simply supported solid timber beam was specifically analysed and designed using WOODexpress [15] software in accordance with the provisions of Eurocode 5 [4]. Solid timber, of strength class C27 was assumed [6]. The coefficient of variation of Nigerian solid timber strength variables is in the range of 0.08 to 0.24 (Appendix 1) as reported by the research unit of Cirad [5]. This was fully accommodated in the reliability-based design process. Safety indices and the material safety factors for solid timber were generated based on the principles of First Order Reliability Method (FORM) using specialized reliability-based code calibration software (CodeCal) developed by the JCSS [8].

FIRST ORDER RELIABILITY METHOD (FORM)

The aim of structural design is to ensure the applied action is greater than the structural resistance, that is:

$$Z = R - S \geq 0 \tag{1}$$

Where R is the structural resistance, S is the load effect and Z is the safety margin. This is based on deterministic approach. However the probability of failure is best established by modeling the uncertainties associated with each of the variables that defined the applied load and structural resistance. This reliability-based approach is adopted in this research.

The probability of failure of the structure is given by the convolution integral [16, 17].

$$P(Z < 0) = \int_{-\infty}^{0} f_Z(\xi)d\xi \tag{2}$$

$$= \Phi(-\beta) \tag{3}$$

$$\text{where } \beta = \frac{\mu(Z)}{\sigma(Z)} \tag{4}$$

Where $f_Z(\xi)$ is probability density function of Z, $\Phi(-\beta)$ is standard normal distribution for the variable β, and β is the safety index which is simply a measure (in standard deviation) of the distance that the mean μ_G is away from the safety-failure interface.

It is supposed that the reliability function can be linearised, so a tangent plane in a point on its surface can be expressed by a first order Taylor series expansion (the basis of FORM).

$$Z_{Lin} = Z(X^*_1, X^*_2, \ldots X^*_n) + \sum_{i=1}^{n} \left(\frac{\partial Z}{\partial X_i}\right)_{X_i = x^*_i} \cdot (X_i - X^*_i) = 0 \tag{5}$$

where

Z_{Lin} = linearised reliability function Z is linearised in $(X^*_1, X^*_2, \ldots X^*_n)$

n = number of stochastic variables in the reliability function

$\left(\frac{\partial Z}{\partial X_i}\right)_{X_i = x^*_i}$ = partial derivative of Z, with respect to $X_i - X^*_i$

The mean value and the standard deviation of Z_{Lin} are

$$\mu_{Lin} = Z(X^*_1, X^*_2, \ldots X^*_n) + \sum_{i=1}^{n} \left(\frac{\partial Z}{\partial X_i}\right)_{X_i = x^*_i} \cdot (\mu_i - X^*_i) = 0 \tag{6}$$

and

$$\sigma_{ZLin} = \sqrt{\left(\sum_{i=1}^{n} \left(\frac{\partial Z}{\partial X_i}\right)^2_{X_i = x^*_i} \sigma_{xi}^2\right)} \tag{7}$$

The probability of failure can be approximated by equation 8:

$$P(Z < 0) = \int_{-\infty}^{0} f_{ZLin}(\xi)d\xi \tag{8}$$

$$= \Phi(-\beta) \tag{9}$$

$$\text{Where } \beta = \frac{\mu(Z_{Lin})}{\sigma(Z_{Lin})} \text{ (is the reliability index)} \tag{10}$$

RELIABILITY-BASED CODE CALIBRATION

Reliability analysis of structures for the purpose of code calibration requires that the relevant failure modes be represented in terms of limit state functions [18]. The limit state functions define the realisation of resistance parameters, and the load varioables resulting in structural failure. In EC5, design equations are prescribes for the verification of the capacity of different modes of failure. The typical format for the verification of a structural timber component with one variable load in EC5 is given as a design equation in the following form:

$$G(x) = k_{mod} Z_d \frac{R_k}{\gamma_m} - (\gamma_g G_k + \gamma_q Q_k) \quad (11)$$

Where k_{mod} is a modification factor taking into account the effect of duration of load and moisture, Z_d is a vector of design variables (e.g. cross section of a timber beam), R_k is the characteristic value of the resistance, γ_m is the partial safety factor for member strength, γ_g and γ_q are the partial safety factors for dead and variable loads respectively, G_k and Q_k are the dead and variable load effects respectively.

According to equation11, failure F corresponds to an event desfined by $F = \{G \leq 0\}$. The partial safety factors together with the characteristic values are introduced in order to ensure a certain minimum reliabiility level for the structural component designed according to equation 11.

The aim of reliability based code calibration, is the calibration of partial safety factors such that the reliability corresponding to different typical design situations are as close as possible to a specified value for the target reliability. Recommendations for suitable target reliabilities, β_t are provided [14]. $\beta_t = 3.8$, is recommended for a 50 year regference period, and $\beta_t = 4.8$, for a one year reference period.

The CodeCal software considered different design situations, through different contributions of different load effects. For two load effects due to permanent and variable load respectively, a factor α_i is used.

$$\alpha_i = \frac{i}{L} \qquad i = 1,2,\ldots L \quad (12)$$

$$G(x) = Z_d \frac{R_k}{\gamma_m} - \alpha_i \gamma_g G_k - (i-\alpha_i)\gamma_q Q_k = 0 \quad (13)$$

Accordingly, the following optimisation problem can be formulated.

$$\min W(\gamma) = \sum w_i(\beta_i(\gamma) - \beta_t)^2 \quad (14)$$

where β_t is the reliability index corresponding to the target reliability, $\beta_i(\gamma)$ is the reliability index corresponding to a design performed with a set of partial safety factors γ and w_i, $i = 1,2, \ldots, L$ are factors indicating relative frequency/importance of the different design situations.

In this study three critical failure modes [19] of a simply supported timber beam (Fig. 1) were considered as follows:

Failure due to excessive shear stress in the beam
Failure due to excessive bending stress in the beam, and
Failure due to excessive compressive stress parallek to the grain.

In the Calibration process, the member strength, dead load effects, variable load effects and the model uncertainties were considered as random variables.

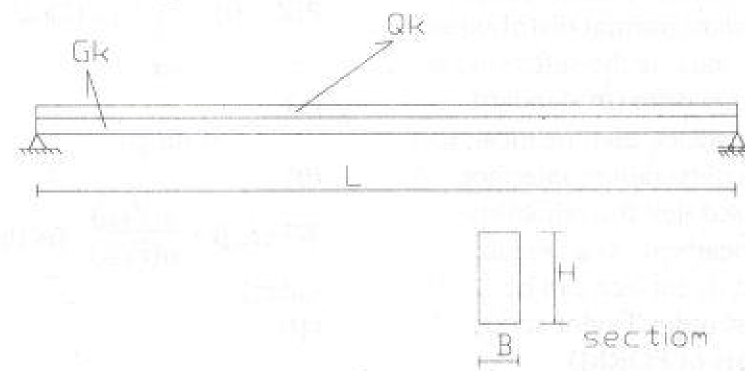

Fig. 1 Simply Supported Timber Beam Subjected to Dead and Variable Loads

The design of the beam was undertaken using WOODexpress [15] software based on the recommended safety factors in the EC5, considering timber strength class C27. Design variables that saftisfied both the ultimate and serviceabiliioty limit states were established, and based on these, the probabilistic and the deterministic variables were presented (Table 1). The distribution models and coefficient variation of load actions and model uncertainties were taken from the JCSS [8]. The coefficient of variation of the solid timber strengths were based on the data generated for the Nigerian timber species [5]. The calibration of the partial safety factors for solid timber in Nigeria (γ_m) were undertaken using the CodeCal Package.

Table 1: Design Variables of the Simply Supported Solid Timber Beam Designed based on the EC5 (Strength Class is C27)

Variable (x)	Unit	Variable type	Distribution Model	Expected Value	Coefficient of Variation
Depth (H)	mm	Deterministic	-	200.0	-
Width (B)	mm	Deterministic	-	50.0	-
Length (L)	m	Deterministic	-	3.0	-
Bending Strength (f_m)	N/mm^2	Probabilistic	Lognormal	27.0	0.05-0.30
Compressive Strenth Parallel to Grain (f_c)	N/mm^2	Probabilistic	Lognormal	22.0	0.05-0.30
Shear Strength (f_v)	N/mm^2	Probabilistic	Lognormal	2.8	0.05-0.30
Dead load (G_k)	kN/m^2	Probabilistic	Normal	0.5	0.05
Variable Load (Q_k)	kN/m^2	Probabilistic	Gumbel	1.5	0.40
Model Uncertainty	-	Probabilistic	Lognormal	1.0	0.1

RESULTS AND DISCUSSION

Fig 2 to 4 shows the relationship between safety index and the contribution of load effect (α), for shear, bending and compression failure modes respectively. For the shear failure mode, safety at all the values of the coefficient of variation of the shear strength investigated, were below the target safety index $\beta t = 4.8$, except for the lowest coefficient of variation, when the the contribution of dead load effect is 0.84 and above. However, when target safety index is 3.8, only the safety indices corresponding to coefficient of variation of shear strength equal to 0.25 and o.30 fall below the taget values. At coefficientt of variation equal to 0.15 and 0.20, safety indices fall below the target value of 3.8 when the contribution of the dead load effect is above 0.96 and 0.90 respectively. At the coefficient of variation equal to 0.05 and 0.10, the safety indices were above the target value of 3.8 for all the values of α. Similar Trens were observed for the bending and compression failure modes. The marked variation of safety indices with coefficient of variation of the timber strength raised a question on the adoption of single partial safety coefficient on 1.3 for solid timber currently being used in the the design of solid timber mebers based on the EC5. The material safety factors need to be a function of the coefficient of variation of the member strength.

Fig. 5 to 7 show the variation of safety indices with the coefficient of variation of member strength for shear, bending and failure mode due to excessive compression strength parallel to the grain. These were summarised in Table 2. It is clear from the plots, that material safety factors is dependant on both the target reliability and the coefficient of variation of member strengtrh. The generated material safety coefficients are the same for all the failure modes.

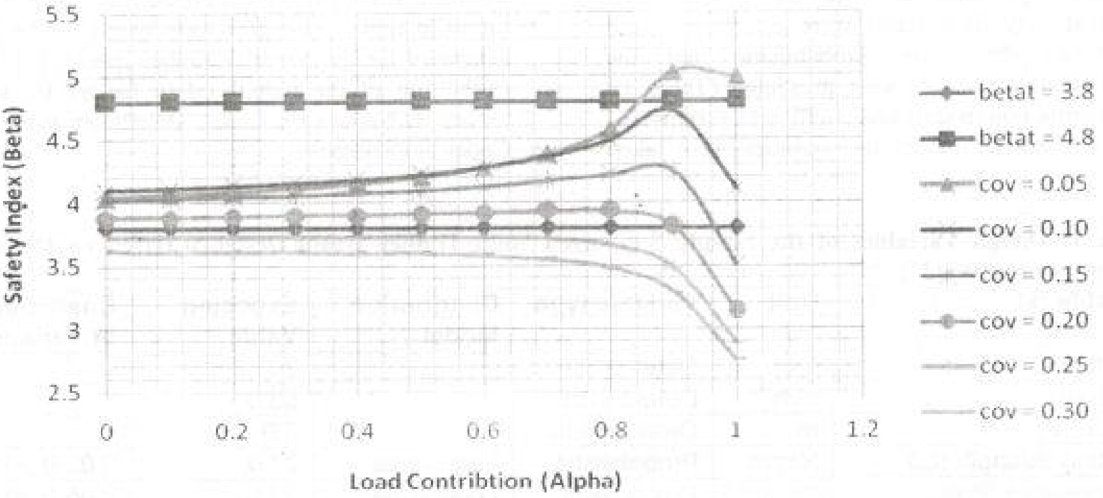

Fig. 2 Variation of Safety Index with Load Contribution (α) for Failure due to Excessive Shear Stress

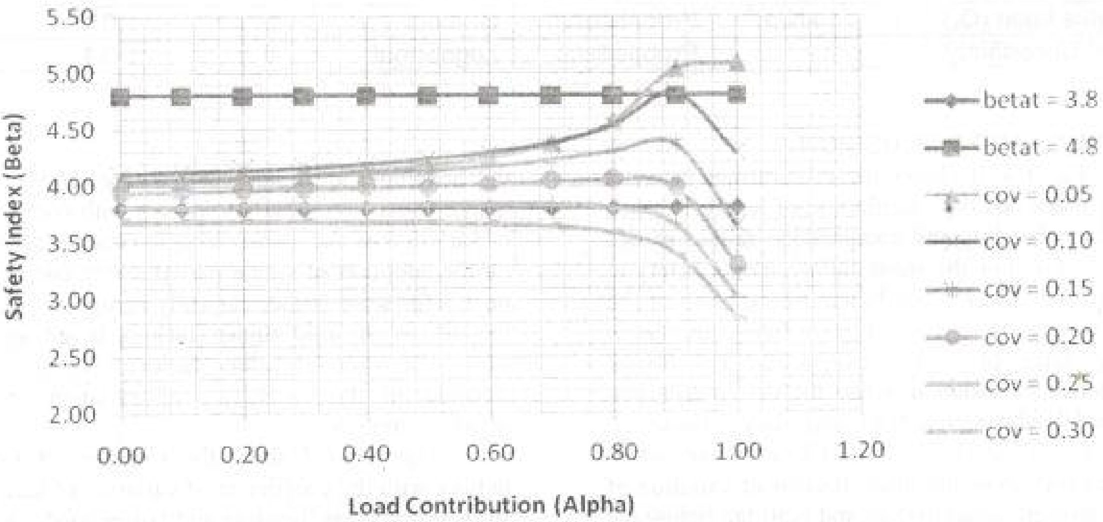

Fig. 3 Variation of Safety Index with Load Contribution (α) for Failure due to Excessive Bending Stress

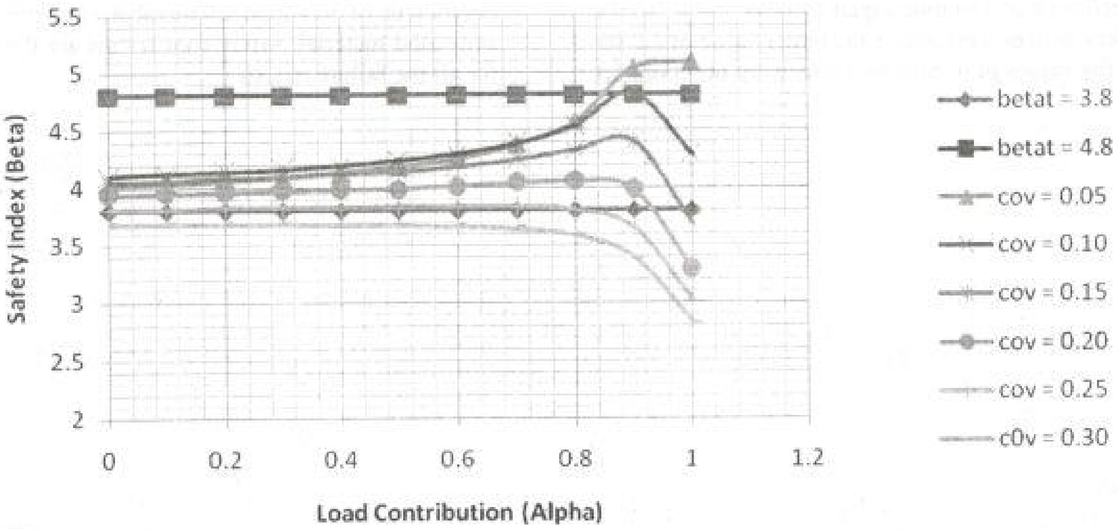

Fig. 4 Variation of Safety Index with Load Contribution (α) for Failure due to Excessive Compressive Stress Parallel to Grain

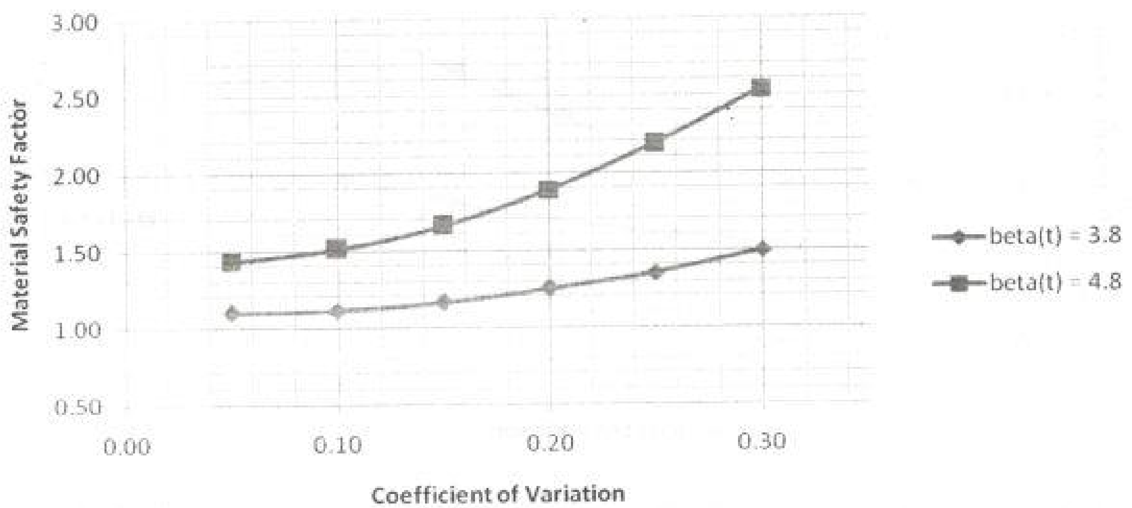

Fig. 5 Material Safety Factor γ_m Against Coefficient of Variation of Shear Strength of the Beam

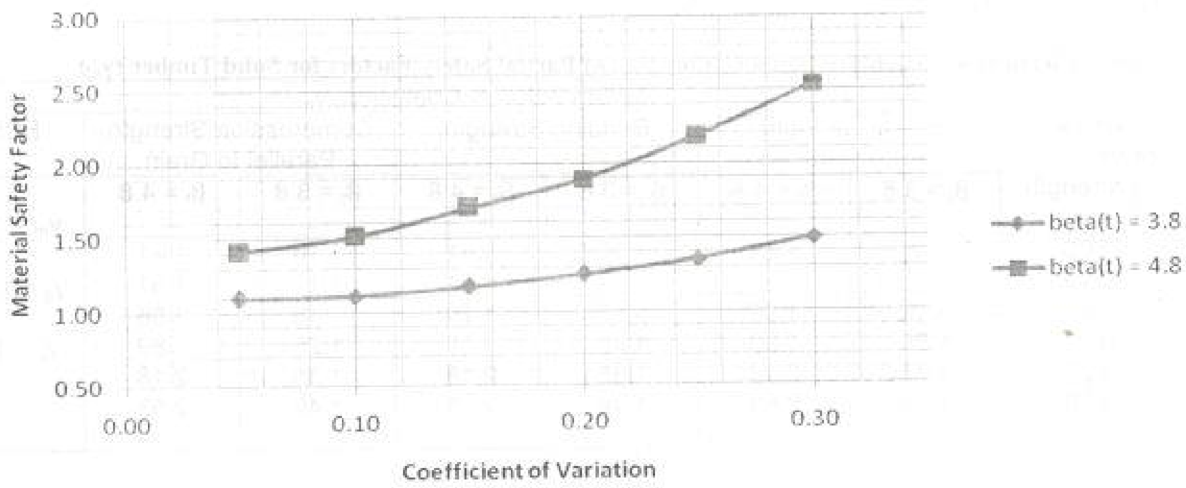

Fig. 6 Material Safety Factor γ_m Against Coefficient of Variation of Bending Strength of the Beam

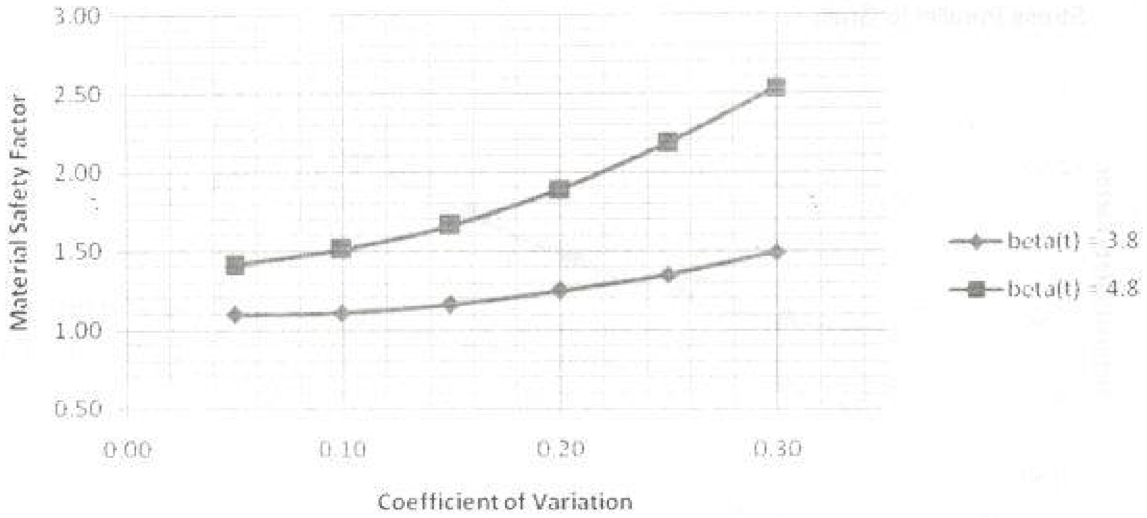

Fig. 7 Material Safety Factor γ_m Against Coefficient of Variation for Compression Strength Parallel to Grain of the Beam

Table 2: Results of Reliability-based Calibration of Partial Safety Factors for Solid Timber (γ_m)

Coefficient of Variation of Strength	Material Safety Coefficient γ_m						
	Shear Strength		Bending Strength		Compression Strength Parallel to Grain		EC5
	$\beta_t = 3.8$	$\beta_t = 4.8$	$\beta_t = 3.8$	$\beta_t = 4.8$	$\beta_t = 3.8$	$\beta_t = 4.8$	
0.05	1.10	1.43	1.10	1.41	1.10	1.41	$\gamma_m = 1.3$
0.10	1.11	1.51	1.11	1.51	1.11	1.51	$\gamma_g = 1.35$
0.15	1.16	1.66	1.17	1.70	1.16	1.66	
0.20	1.25	1.89	1.25	1.89	1.25	1.89	$\gamma_q = 1.5$
0.25	1.35	2.18	1.35	2.18	1.35	2.18	
0.30	1.49	2.53	1.49	2.53	1.49	2.53	

CONCLUSION

Partial Safety factors for the design of solid timber according to EC5 were generated in this study using probabilistic method. The inherent variability strength of solid timber species in Nigeria, made available by the research unit of Cirad [5] were considered in the reliability-based calibration. Solid timber beam design using WOODexpress [15] according to the safety format presented in EC5 was considered. The Calibration of the material safety coefficients were undertaken using CodeCal of JCSS [8]. The generated partial safety factors for solid timber should be used in order to achieve a uniform and consistent reliability in the design of timber structures in Nigeria. It is also recommended that the EC5 should fully replace the widely used permissible stress method in Nigeria, in order to join the advanced nations in the field of timber structural design.

REFERENCES

(1) NCP2 *Timber Design Manual*, Nigerian Industrial Standard Publication, 1973.

(2) CP112 *The Structural use of Timber*, British Code of Practice, British Standard Institution, London, 1967

(3) BS5268 *Structural use of Timber*, Code of Practice for Permissible Stress Design, Materials and Workmanship, British Standard Institution, London, 2002

(4) Eurocode 5 *Design of Timber Structures*, European Standard ENV 1005-1-1: General Rules and rules for Buildings, CEN, European Committee for Standardisation, Brussels, Belgium, 2004.

(5) Cirad *Tropix-African Wood*, The Production and Processing of Tropical Woods, Research Unit of Cirad (Centre de Cooperation Internationale en Recherche Agronomique pour le Development, 2004. http://tropix.cirad.fr/africa/africa.html. Retrieved on 26th February, 2010

(6) EN 338 (2008) Structural Timber – Strength Classes.
(7) Glos, P. *Strength Grading*, In Timber Engineering STEP 1, pp A6/1-A6/8. Centrum Hout, The Netherlands, 1995b
(8) JCSS *Probabilistic Model Code: Material Properties (Timber)*, Joint Committee on Structural Safety. 12th draft, 2006
(9) Glos, P. *Solid Timber – Strength Classes*, In Timber Engineering STEP 1, pp A7/1- A7/8. Centrum Hout, The Netherlands, 1995a
(10) Ravenshot, G., van der Linda, M., Vrouwenveider, T. and Kuilien, W. *An Economic Method to Determine the Strength Class of Wood Species*, HERO, Vol. 49, No. 4, 2004
(11) Baltrusaitis, A and Pranckevicene, V. *Strength Grading of the Structural Timber*, Material Science Journal, Vol. 9, No 3. 2003, pp 284-287
(12) Antti, H. Ranta-Maunus, A. and Goran, T. *Potential of Strength Grading of Timber with Combined Measurement Technique*. Report of the Cambridge Project – Phase 1, 2006
(13) Ridley-Ellis D., Moore J., and Lyon A. *Strength Grading and the End User Lessons from the SIRT Project at Napier University*, Conference COST E53, 29-30th October, 2008, Delft, the Netherlands.
(14) Eurocode0 (2002). Basis of Structural Design, Brussels, 2002
(15) WOODexpress (2009). Design of Timber Structures to Eurocode 5. RUNET
(16) Melchers R. E. *Structural Reliability Analysis and Prediction*, John Willey and Sons, New York, 1999
(17) Ditlevsen, O. and Madsen, H. O. *Structural Reliability Methods*, Internet Edition, 2005
(18) Faber, M. H. and Sorensen, J. D. *Reliability-Based Code Calibration - The JCSS Approach*, Proceedings to the 9th International Mechanisms for Concrete Structures In Civil Engineering ICASP, San Francisco, USA, 2003
(19) Afolayan, J. O. *Probability-Based Design of Glued Thin-Webbed Timber Beams*, Asian Journal of Civil Engineering Vol. 6. No 5, 2005, pp 75-83

APPENDIX 1 STANDARD DEVIATION OF STRENGTH PARAMETERS OF SOME SELECTED TIMBER SPECIES IN NIGERIA

Solid Timber Specie	Bending Strength (N/m^2)		Shear Strength (N/m^2)		Compression strength Parallel to the grain (N/m^2)	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Abokpo	130.00	31.00	9.82	2.34	44.69	8.53
Agba	74.00	15.00	6.26	1.27	34.68	5.62
Agboin	98.00	13.00	7.83	1.04	39.36	4.18
Ahun (Awun)	43.00	6.00	4.05	0.57	27.17	3.03
Akomu	63.00	13.00	5.50	1.14	32.26	5.33
Apa Igba	124.00	23.00	9.46	1.75	43.75	6.49
Apaya	94.00	15.00	7.58	1.21	38.63	4.93
Apopo	72.00	13.00	6.12	1.11	34.26	4.95
Araba	36.00	8.00	3.52	0.78	25.08	4.46
Arere (Obeche)	52.00	9.00	4.72	0.82	29.59	4.10
Aye	143.00	10.00	10.60	0.74	46.65	2.61
Ayinre ogo	81.00	14.00	6.73	1.16	36.12	4.99
Black Afara (Idigbo)	71.00	12.00	6.05	1.02	34.04	4.60
Dunki (diana)	113.00	16.00	8.78	1.24	41.96	4.75
Ekpagoi eze	137.00	13.00	10.24	0.97	45.76	3.47
Ekpagoi	93.00	17.00	7.51	1.37	38.44	5.62
Enoi	63.00	6.00	5.50	0.52	32.26	2.46

Erun (Sasswood)	128.00	19.00	9.70	1.44	44.38	5.27
Gedu Nohor	80.00	12.00	6.66	1.00	35.92	4.31
Ibagho	95.00	8.00	7.64	0.64	38.81	2.61
Kefe (poroposo)	96.00	16.00	7.71	1.28	38.99	5.20
Lolagbola	88.00	13.00	7.19	1.06	37.50	4.43
Obonbo Nekwi	95.00	14.00	7.64	1.13	38.81	4.58
Odoko	94.00	12.00	7.58	0.97	38.63	3.94
Ofun	110.00	10.00	8.59	0.78	41.46	3.02
Ogiovu	58.00	6.00	5.15	0.53	31.08	2.57
Okan	134.00	23.00	10.06	1.73	45.31	6.22
Okoko	100.00	15.00	7.96	1.19	39.72	4.77
Okwen	93.00	13.00	7.51	1.05	38.44	4.30
Heavy Sapele	87.00	14.00	7.12	1.15	37.30	4.80
Opepe	95.00	11.00	7.64	0.88	38.81	3.60
Osun	116.00	24.00	8.97	1.86	42.46	7.03
Otutu	120.00	20.00	9.21	1.54	43.11	5.75
Owewe	103.00	19.00	8.15	1.50	40.25	5.94
Akuk	77.00	13.00	6.46	1.09	35.31	4.77
Ayan (Ayanran)	116.00	13.00	8.97	1.00	42.46	3.81
Eba (Ekki)	162.00	21.00	11.71	1.52	49.35	5.12
Guibourtia	127.00	16.00	9.64	1.21	44.23	4.46
Ovbialele	115.00	18.00	8.90	1.39	42.29	5.30
Olazo	105.00	11.00	8.28	0.87	40.60	3.40
Oziya	66.00	12.00	5.71	1.04	32.94	4.79
Sapele	102.00	11.00	8.09	0.87	40.07	3.46
Utile	91.00	11.00	7.38	0.89	38.07	3.68
Vene	130.00	14.00	9.82	1.06	44.69	3.85
White Afara (Afara)	80.00	16.00	6.66	1.33	35.92	5.75

(SOURCE, Cirad, 2009)