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Design of selected wood species for longer span trusses

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Abstract

The trends of researches in the built industry are exploration of the available alternatives; either as raw materials or finished products construction materials, to most construction materials that have been playing dominant roles in construction industry for decades. Aside that the cost of using them in construction keep rising, the associated health hazards in their production and usage are huge and costly to rectify. The usage of locally available construction materials is being hindered by the lack of useful engineering data of the materials for structural design. Wood is an alternative local, green and sustainable material to steel in roof truss design and construction. Its usage has been limited to short span roof trusses based on inherited knowledge especially in Africa. There is need to know the actual capacity and potential of various wood species in relation to roof design. This work studied the properties of; *Gmelina arborea, Tectona grandis* **(Teak)**, *Terminalia superba* **(Afara)**, Ayin *(Anogeissus leiocarpus*), *and Acacia (Robinia pseudoacacia*). The values obtained from the laboratory experiments conducted on them were used to design rafter and tie beam of king post roof truss spanned to 12 m and 8 m using timber section 0f 50 mm x 150 mm of all the species. Then section sizes of 150 mm x 250 mm and 250 mm x 350 mm of *Acacia* were then designed separately. It was found that the five species were not suitable for long span roofing using the chosen three section sizes because the tie beams failed in deflection, which is most critical to deliver a safe, durable and serviceable roof. However, all the species, except Afara, are satisfactory for rafter whose span is not more than 7.5 m. It was also discovered that the higher the section size of timber used in the design the lower the deflection.

Keywords: Trusses; Long span; Density; Mechanical properties; King Post

1. Introduction

One of the important factors to measuring the growth of any nation is the level of infrastructural development of such nation. Nations, most especially developing ones like Nigeria, need to rely on their locally available raw materials for their effective and efficient construction activities at relatively low cost, in order to achieve sustainable industrialization and growth [1, 2, 3, 4, 5]. One **of** the raw materials that is in abundance in Nigeria is timber, which is wood in the form that is suitable for construction of carpentry, joinery or for reconversion for manufacturing purposes [6]. Structural timber is the timber used in framing load-bearing structures [2, 4, 7]. There are globally acceptable two (2) classes of wood; hardwoods and softwoods [8, 9]. Its usage for construction is very much on the increase because it is sustainable, renewable, light, easy to handle, possess good workability, versatile, high thermal insulative, high elasticity, durable, aesthetic, save time and it is environmentally friendly as it constitutes no health hazard and environmental challenge to the world like cement [1, 3, 4, 5, 10, 11, 12].

There are numerous varieties **of** wood species useful for different purposes [9] with no useful information for designers to work on. Hence, taking right decision on their usage for design and construction is difficult [3, 4]. Therefore, rigorous researches have to take place in this direction [2]. Some of the researched timbers are; *Gmelina arborea, Parkia biglobosa*

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and Prosopis Africana [9], Teak and Ebony [3], ***Meliceae excelsa*** (Iroko), Mahogany (***Khaya ivorensis***), Obeche, ***Afzelia Africana*** (Apa) and ***Celtis Mildbraedii*** (Ita) [13], ***Azadirachita Indica*** and ***xylopia aethiopica*** [2], *Holarihena Floribunda* and *Nesogordonia Papaverifera* [14], Heartwood and Sapwood [15], *Anogeissus Leiocarpus* [16].

Engineers and related professionals must pay adequate attention to the structural (mechanical) properties of wood [17]. It is, therefore, imperative for Engineers to have adequate information on the various available species to be able to effectively and efficiently use them to design safe, durable, serviceable and stable timber structure at a reduced cost. The more the data readily available to design Engineers, the less the risks of failure of the designs and construction [2] and the more the confident they have in embracing the use of such material. Physical and mechanical properties of small clear (free of defects and straight) specimen of timber species must be obtained from laboratory tests of the wood samples [13, 18]. Apart from wood defects, types of loads, loading conditions, duration of loading, wood species and environmental factors are other factors that can influence the strength **of** wood [2, 13].

Physical properties of wood are the quantitative features of wood that are influential to its responses to external influences other than applied forces [13]. Some of the physical properties are; density, specific gravity, percentage volume shrinkage, percentage volume swelling and void volume percentage. Application of timber for structural works is dependent on its strength, which is a function of wood density [19]. That is, the higher the density of wood, the stronger the wood [13]. Density is, therefore, very important in the evaluation of mechanical properties of wood species [19].

Mechanical properties of wood are features with which it reacts to or resist externally applied forces that are capable of distorting the shape and size of timber [13, 20]. Mechanical properties are modulus of rupture (MOR), modulus of elasticity (MOE), compression, tension, bending and shear strength [21]. [13] grouped these into; elastic properties (resistance to deformation and distortion), strength properties (ultimate resistance to applied loads) and flexural (bending) properties which are induced in woods when they are used as a beam as in floor or rafter systems. The values of mechanical properties of wood are not the same in the three principal (longitudinal, tangential and radial) axes of the wood because of anisotropism of wood [13**]**. It further explained that the value is higher in the longitudinal axis than the tangential and radial axes. These wood properties in the code were designed relative to the wood species available in the country of the code origin. Wood properties need to be obtained for each location for effective application of such wood especially when such usage is geared towards structural application. The end data of such work will help in further research and in locally design of code of standard.

1.1. Theoretical Background of the Study

Although**,** there are many dictating factors on the choice of species, the species' grade stresses are of utmost consideration [21]. Grade stress has been defined in section 1.3.6 of [21] and section 2.1 of [22] as the stress which can safely be permanently sustained by material of a specific section size and of a particular strength class or species grade. Section 2.3 of [22] described permissible stress as the stress that can safely be sustained by a structural material under a particular condition. It is estimated by multiplying grade stress by appropriate modification factors for section size, service and loading [22].

The design reco mmendations of BS 5268-7.1:1989 are based on engineer's bending theory which is in consonant with the reco mmendations of [21]; the method, which ensures that the permissible bending stress, shear stresses and deflection are not exceeded.

Shear modulus (Shear strength) and longitudinal modulus of elasticity of timber are of utmost importance in the proper, adequate and accurate evaluation of timber structure performance [17]. BS 5268-7.1:1989 gives the permissible shear stress τ_{adm} (in N/ mm^2) as;

$$\tau_{adm} = \tau_g \times k_3 \times k_8$$

$$\therefore if\ expanded, \tau_{adm} = \frac{3}{2}\frac{FL}{2bh} \qquad (BS\ 5268-7.1{:}\ 1989)$$

Where,

τ_g is the grade shear stress (in N/ mm^2), k_3 is the load duration modification factor, k_8 is the load sharing modification factor, F is total load per metre length, L is Effective span, b is breadth section, and h is depth of section.

The permissible bending stress $\sigma_{m,adm}$ (in N/ mm^2) is Equation is given by [22] as,

$$\sigma_{m,adm} = \sigma_{m,g} \times k_3 \times k_7 \times k_8$$

$$\therefore if\ expanded, \sigma_{m,adm} = \frac{M}{Z} \qquad (BS\ 5268 - 7.1{:}\ 1989)$$

Where,

$\sigma_{m,g}$ is the grade bending stress (in N/ mm^2), k_3 is the load duration modification factor, k_7 is the section depth modification factor, k_8 is the load sharing modification factor, M is bending moment, and Z is section modulus.

[13] defined MOE as the load carrying capacity of member in bending and it is also proportional to maximum moment borne by the wood species. While MOR is used as wood strength indicator [13] and suitable for furniture and structural applications [23], MOE indicates that a deformed material due to low stress can be recovered when the applied load is removed [13] and useful for structural purposes regardless of their location and age [2, 23]. [2] explained that the use of timber for structural design and construction is limited by the stiffness properties (MOE).

Section 1.3.13 of [21] explained that MOE together with the values of grade stress and density are the basis upon which timbers are classified. Section 1.6.7 of [21] stated that MOE, like other properties of timber such as bending, tension and compression stresses, is dependent on the section sizes and size related grade effects. Section 2.9 of [21] stated that the mean MOE should be used to calculate deflections and displacements under both dead and imposed loads unless the imposed load is for an area intended for mechanical plant and equipment, or for storage, or for floors subject to vibrations, e.g., gymnasia and ballrooms, in which case the minimum MOE should be used.

Hardness is one of the most important mechanical properties of wood for consideration in its use for building construction [24]. [25] stated that surface hardness is the most important hardness type for consideration in the use of wood in building construction industries. Hardness of timber can be evaluated with the use of either destructive methods; Janka hardness test and Brinell hardness test, or nondestructive method [24, 26].

Section 2.11 of [21] explained that when timber members are subjected to compression in the direction of the grain, the permissible stresses of the timber members are influenced by the particular conditions of service and loading stated in sections 2.6.2, 2.8 and 2.9 of [21]. Whenever the direction of the load is inclined to the grain at an angle, Section 2.7 [21] stated the permissible compression stress for the inclined surface should be found from Equation;

$$\sigma_{c,adm,a} = \sigma_{c,adm,II} - (\sigma_{c,adm,II} - \sigma_{c,adm,\perp}) sina$$

Where;

$\sigma_{c,adm,II}$ is the grade stress parallel to the grain and modified appropriately for moisture content and/or duration of loading.
$\sigma_{c,adm,\perp}$ is the grade stress perpendicular to the grain and modified appropriately for moisture content and duration of loading
α is the angle of inclination

One of the important elements of building is roof, which is the uppermost part of building, provides cover to the entire building from weather, protects the occupants of such buildings from weather [27]. It submitted that until roof is in place on a structure, it cannot be completely called building. Truss is an assemblage of long slender structural elements that are connected at their ends [27, 28]. There are several types of roof truss in practice but an acceptable roof truss must be able to fulfill certain conditions; aesthetic (beautiful shape and configuration), economy (relatively cheap), safety (satisfactory in deflection) and stable (all the joints must be balanced, remain in position and not fail under load).

2. Material and methods

2.1. Research Materials and Research Area

The research materials are five (5) hardwood species; *Gmelina arborea*, *Tectona grandis* **(Teak)**, *Terminalia superba* **(Afara***)*, Ayin ***(Anogeissus leiocarpus***)*, and Acacia* (*Robinia pseudoacacia*). The research area is South West Region of

Nigeria which is on Longitude 8.6753^0 E and Latitude 9.082^0 N (www.distancesfrom.com). These species are available in abundance in the research area.

2.2. Research Methods

The wood samples had been air-dried for two months as at the time of collection. They were tested for physical properties; density, specific gravity, void volume percentage and moisture content, and mechanical properties; MOR, MOE, bending strength test, toughness test, hardness test, compressive strength and shear strength tests. The standards used for the experiments are [18, 29]. The results obtained from the experiments were thereafter used to design each of the species for long span roofing with focus on rafter and tie beam of the roof type. The chosen roof type is king post.

The rafter was checked for bending, compression, slenderness and combined bending and compression at the span while it was checked for bending, compression and combined bending and compression at the support of the rafter. Similarly, the tie beam was designed for tension, bending, deflection and combined tension and bending at its span while tension, bending and combined bending and tension were checked at the supports of the tie beam. All the species were checked for shear capacity. This is to verify the applicability of the selected wood species to long span roof trusses. The structural analysis and design were done manually. The design was done in accordance to [21]. The code affirmed that Equation 3.10 must be satisfied if the design of timber for strength (axial tension, axial compression, bending or shear strength) requirement must be satisfied.

$$Applied\ stress \ \leq \ Permissible\ stress \ \ldots\ldots..3.10$$

Where generally, permissible stress is defined by **E**quation 3.11

$$Permissible\ stress, \sigma_m \ = Grade\ stress\ (\sigma_g) \times \ K_2 \ \times K_3 \ \times K_6 \ \times \ K_7 \ \times K_8\ ,, \ldots\ldots..3.11$$

Where;
K_2 is moisture content of the timber Table 1 and Table 16 of [21];
K_3 is duration of the load on the timber in Clause 1.6.6, clause 2.8 and Table 17 of [21];
K_6 is shape of the cross-section of the element being considered Clause 2.10.5 of [21];
K_7 is depth of the section being considered Clause 2.10.6 of [21];
K_8 is existence of structural elements enabling load sharing Clause 2.9 of [21]

2.3. Joints and Effective Area of Cross-Section

Since design of long span roof is of concern in this research work and the standard length of timber is not more than 3600 mm long, hence there is need for jointing. Design of joints in this work was based on the provisions of section 6 of [21]. Section 6.4 of [21] deals with nailed joints which was used for the design in this work. The Effective area of cross-section was in accordance to Section 6.4.2 of [21] while the spacing of nail was in strict compliance to Section 6.4.3 of [21].

3. Results and discussion

3.1. Results of Laboratory Experiments

The values obtained from the laboratory experiments for the compressive strength, tensile strength, bending strength, shear strength, which are the compression parallel to grain, tensile parallel to grain, bending parallel to grain and shear parallel to grain of the wood species are shown in **Table 1**. These are otherwise referred to as grade stresses of the species. The table also contain other useful design data such are the MOE and density of all the tested species.

Table 1 Grade Stresses of the Tested Species Obtained from Laboratory Tests with their Densities and Moduli of Elasticity

Design parameters	**Species**				
	Afara	**Ayin**	**Gmelina**	**Teak**	**Acacia**
Compression parallel to grain (N/ mm^2)	2.431	53.240	28.581	19.603	31.828
Tension parallel to grain (N/ mm^2)	11.140	62.215	26.903	26.691	82.681
Bending parallel to grain (N/ mm^2)	34.147	90.438	65.039	51.239	66,990
Shear parallel to grain (N/ mm^2)	1.413	2.596	2.371	3.816	2.650
Modulus of Elasticity (N/ mm^2)	1868.518	2815.821	3071.113	1648.929	2713.723
Density (kg/m^3)	656.670	766.670	710.000	810.000	1063.330

3.2. Discussion of Results of Roof Truss' Design Using the Tested Species' Parameters

The results of the experiments in **Table 1**, being the values of the mechanical properties of the tested species; *Anogeissus leiocarpus* (Ayin), *Acacia* (*Robinia pseudoacacia*), *Gmelina arborea, Tectona grandis* (Teak) and *Terminalia superba* (Afara), were used to carry out design of King post roof type to [21]. The roof was first designed with the tie beam spanned to 12 meters and later reduced to 8 meters. **It suffices to add that a roof is said to be long span if the span is not less than 12 metres [30].** The design was centered on two roof elements; the rafter and the tie beam. The responses of the elements at their spans and at their supports to loadings using timber section 50 mm x 150 mm of all the species first, then 150 mm x 250 mm and 250 mm x 350 mm sections of *Acacia* (*Robinia pseudoacacia*) only were noted and recorded. For the two roof truss' spans, the rafters were checked for bending, compression, combined bending and compression while the tie beams were checked for deflection, tension, bending, combined bending and tension. The slenderness of the chosen sections was also checked.

3.2.1. Rafter

Generally, this element of roof is in compression. Timber section for this element should be able to conveniently resist any induced compression by the loading effects on the roof. Section 50 mm x 150 mm in rafter of 7.5m long using *Anogeissus leiocarpus* (Ayin), *Acacia* (*Robinia pseudoacacia*) and *Gmelina arborea* were satisfactory in compression and bending while the same section for the same length of rafter using *Tectona grandis* (Teak) and *Terminalia superba* (Afara) failed in compression and bending.

All the species failed in combined bending and compression when the same section (50 mm x 150 mm) of 7.5m rafter were checked for it (combined bending and compression). At the supports of the 7.5m rafter, the section (50 mm x 150 mm) of all the species, except *Terminalia superba* (Afara), were satisfactory in bending, compression and combined bending and compression. Although, *Terminalia superba* (Afara) was satisfactory in bending and compression at the supports it failed in combined bending and compression. When the roof was spanned to 8m, the rafter became 6.02m. With this length of rafter, it was only *Terminalia superba* (Afara) that failed under bending and compression while the remaining species; *Anogeissus leiocarpus* (Ayin), *Acacia* (*Robinia pseudoacacia*), *Gmelina arborea,* and *Tectona grandis* (Teak) were satisfactory. That is *Tectona grandis* (Teak) that failed in bending and compression when the length of the rafter was 7.5m passed when the length of the rafter was reduced to 6.02m with same section of timber.

All the species failed when their 6.02m rafter were checked for combined bending and compression. They were all satisfactory in slenderness check. At the supports of the rafter, the species were all satisfactory in bending, compression and combined bending and compression. We can conveniently conclude that timber section 50 mm x 150 mm of *Anogeissus leiocarpus* (Ayin), *Acacia* (*Robinia pseudoacacia*) and *Gmelina arborea* can be used to resist either compression or bending in rafter of not more than 7.5m while *Tectona grandis* (Teak) cannot go more than 6.0m. When the section of timber was increased to 150 mm x 250 mm *Acacia* (*Robinia pseudoacacia*), the rafter was satisfactory in compression, bending, combined compression and bending and at the supports.

3.2.2. Tie beam

When the roof tie beams were of 12m span and the section was 50 mm x 150 mm, all the species were satisfactory in tension but all failed in bending, deflection and combined tension and bending. At the supports of the tie beams, all the species were satisfactory in tension, bending and combined tension and bending. When the tie beams were reduced to

8m, only the tension check was also satisfactory while bending, deflection and combined bending and tension check failed. Hence, the chosen section (50 mm x 150 mm) of all the species is not adequate for the tie beam with span greater than or equal to 8m. When *Acacia* (*Robinia pseudoacacia*) timber section of 150 mm x 250 mm was tried in tie beam of span 12m, the section was satisfactory in tension, bending, combined tension and bending but failed in deflection. When the span was reduced to 8m for the same section 150 mm x 250 mm, the deflection was far better than when it was 12m but was still not satisfactory. The su mmary of the results of the load analysis and subsequent designs are represented in **Table 2** and **Table 3**. From **Table 2** and **Table 3**, the slenderness of the section for all the species was satisfactory. From **Table 2**; A is *Tectona grandis* (Teak), B is *Gmelina arborea,* C is *Anogeissus leiocarpus* (Ayin), D is *Acacia* (*Robinia pseudoacacia*) and E is *Terminalia superba* (Afara).

3.3. Discussion of Shear

All the five (species); *Anogeissus leiocarpus* (Ayin), *Acacia* (*Robinia pseudoacacia*), *Gmelina arborea, Tectona grandis* (Teak) and *Terminalia superba* (Afara), are satisfactory in shear using section 50 mm x 150 mm. This is because the maximum permissible shear of all the species is higher than the applied shear to all the species.

3.4. Discussion of Deflection

Table 4 reveals the su mmary of deflections of the different section of *Acacia* (*Robinia pseudoacacia*) timber. The deflection was very high (24,054.658 mm) with 50 mm x 150 mm section at a span of 12 m. It significantly reduced to 1,732 mm when the section was increased to 150 mm x 250 mm at the same span of 12 m. It was reduced to 378.717 mm when a section of 250 mm x 350 mm was used for the same span. The values of deflections were 4,751.537 mm, 324.123 mm and 74,808 mm for section 50 mm x 150 mm, 150 mm x 250 mm and 250 mm x 350 mm used at **8m** span. This shows that deflection reduces with increase in section of timber used for roof design.

Table 2 Su mmary of Design Outcomes for all the Species

Roof type & span	**Elements designed and span**	**Location**	**Mechanical properties**	**Wood species**				
				A	**B**	**C**	**D**	**E**
King Post (12m)	Rafter 50 x150 mm (7.5m)	Span	Bending	fail	ok	ok	ok	fail
			Compression	fail	ok	ok	ok	fail
			Combined[3]	fail	fail	fail	fail	fail
			Slenderness	ok	ok	ok	ok	ok
		Support	Bending	ok	ok	ok	ok	ok
			Compression	ok	ok	ok	ok	ok
			Combined[3]	ok	ok	ok	ok	fail
	Tie beam 50 x 150 mm (12m)	Span	Tension	ok	ok	ok	ok	ok
			Bending	fail	fail	fail	fail	fail
			Combined[4]	fail	fail	fail	fail	fail
			Deflection	fail	fail	fail	fail	fail
		Support	Bending	ok	ok	ok	ok	ok
			Tension	ok	ok	ok	ok	ok
			Combined[4]	ok	ok	ok	ok	ok
King Post (8m)	Rafter 50 x 150 mm (6.02m)	Span	Bending	ok	ok	ok	ok	fail
			Compression	ok	ok	ok	ok	fail
			Combined[3]	fail	fail	fail	fail	fail
			Slenderness	ok	ok	ok	ok	ok
		Support	Bending	ok	ok	ok	ok	ok
			Compression	ok	ok	ok	ok	ok
			Combined[3]	ok	ok	ok	ok	fail

	Tie beam 50 x 150 mm (8m)	Span	Tension Bending Combined[4] Deflection	ok fail fail fail	ok fail fail fail	ok fail fail fail	ok fail fail fail	ok fail fail fail
		Support	Bending Tension Combined[4]	ok ok ok	ok ok ok	ok ok ok	ok ok ok	ok ok ok

3Combined bending and compression; 4Combined tension and bending

Table 3 Su mmary of Design Outcomes of *Acacia* (*Robinia pseudoacacia*)

Roof type & span	Elements designed and span	Location	Mechanical properties	Remark
King Post (12m)	Rafter 150 x250 mm (7.5m)	Span	Bending	Satisfactory
			Compression	Satisfactory
			Combined[3]	Satisfactory
			Slenderness	Satisfactory
		Support	Bending Compression Combined[3]	Satisfactory Satisfactory Satisfactory
	Tie beam 150 x 250 mm (12m)	Span	Tension Bending Combined[4] Deflection	Satisfactory Satisfactory Satisfactory Not satisfactory
		Support	Bending Tension Combined[4]	Satisfactory Satisfactory Satisfactory
King Post (8m)	Rafter 150 x 250 mm (6.02m)	Span	Bending Compression Combined[3] Slenderness	Satisfactory Satisfactory Satisfactory Satisfactory
		Support	Bending Compression Combined[3]	Satisfactory Satisfactory Satisfactory
	Tie beam 150 x 250 mm (8m)	Span	Tension Bending Combined[4] Deflection	Satisfactory Satisfactory Satisfactory Not satisfactory
		Support	Bending Tension Combined[4]	Satisfactory Satisfactory Satisfactory

3Combined bending and compression; 4Combined tension and bending

Table 4 Values of Deflection Obtained using *Acacia (Robinia pseudoacacia)* of Different Sections for Roof Design

Roof type	**Section**	**Deflection At 12 m**	**Deflection 8 m**
King post	50 mm x 150 mm	24,054.658 mm	4,751.537 mm
	150 mm x 250 mm	1,732 mm	324.123 mm
	250 mm x 350 mm	378.717 mm	74.808 mm

4. Conclusion

Anogeissus leiocarpus (Ayin), *Acacia* (*Robinia pseudoacacia*), and *Tectona grandis* (Teak) are dense and have mechanical properties that suggested that they are very useful structural timber. *Gmelina arborea* and *Terminalia superba* (Afara) are also hardwood but have limited structural use. In fact, they are advisable for use where no structural timber is required. The designs show that the higher the section of timber used for the tie beam the lower the deflection of the tie beam. It also **show** that the lower the span the lower the deflection of the tie beam. None of the species that were investigated was good enough for a long span roof. Because, none of it was satisfactory in deflection (for the chosen sections), which is an important parameter to be satisfied for a safe, durable, serviceable and sustainable roof to be achieved, even at a very high section of 250 mm by 350 mm and a span of 8 metres,

Reco mmendations

Based on the outcomes of this research, the followings are hereby made as reco mmendation;

- *Anogeissus leiocarpus* (Ayin), *Acacia* (*Robinia pseudoacacia*),), *Gmelina arborea* and *Tectona grandis* (Teak), in that order, are reco mmended for; compression members (rafter, king post, column, and strut), tension member (tie beam), combined bending and tension, combined bending and compression. *Terminalia Superba* (Afara) is not reco mmended at all. Section size, cost and span to be covered by the member are also important factors in making decision on the species to be used as reco mmended.
- None of the tested species is reco mmended for usage in the construction of long span tie beam construction.
- *Acacia* (*Robinia pseudoacacia*), *Anogeissus leiocarpus* (Ayin), and *Gmelina arborea* are adequate for rafter length that is not more than 7.5 m while Teak cannot be more than 6.0 m.

Compliance with ethical standards

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Disclosure of conflict of interest

The Authors declared that there is no conflict of interest with respect to the publication of this paper.

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