



LIGHT-FRAME TIMBER AS A REPLACEMENT FOR RE- INFORCED CONCRETE IN LOW-RISE RESIDENTIAL HOUSES IN NIGERIA

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Abstract

African cities are on the frontline of global warming, alongside climate change, and Civil Engineers being the pioneers of built environment, in this part of the world need to start doing more and faster, just like most of the modern cities around the world that are now consciously, slowly evolving towards an environment with net-zero emissions and climate resilient systems. This paper explored the potential for using Opepe hardwood, graded D50 by the Eurocode, as a cost-effective and environmentally-friendly alternative to traditional construction materials for low-rise residential buildings in Nigeria. The study uses Autodesk Robot Structure as the design software for analysis and design, with the ASD method as the design principle. A duplex (5000 sq.m on plan) was analyzed with live loads, wind velocity, load combination, and load duration factors considered. The results show that the use of Opepe hardwood and the application of ASD design principles yielded successful results in the analysis and design of light-frame timber structures. The cost savings and environmental benefits of using timber also make it an attractive alternative to traditional construction materials. It was therefore recommended that; architects, engineers, and builders in Nigeria explore the use of Opepe in their designs and construction projects.

Keywords: Timber, Light-Frame, Opepe, Autodesk RobotStructure 18, Low-Rise Residential Housing.

Introduction

The construction industry is increasingly seeking sustainable and eco-friendly building materials to mitigate the environmental impact of building projects. In this context, the use of light-frame timber as a replacement for reinforced concrete in low-rise residential houses is gaining popularity as a viable option. Light-frame timber construction involves the use of engineered wood products, such as cross-laminated timber (CLT) and glue-laminated timber (Glulam), as structural members. Timber is a renewable resource that has a lower carbon footprint than

reinforced concrete, making it an environmentally friendly option (Ali *et al.*, 2019; Berardi and Ghaffarianhoseini, 2019).

In Nigeria, the use of Opepe, a commonly found Nigerian timber species, in light-frame timber construction is a promising alternative to reinforced concrete. Opepe is hardwood specie with high mechanical properties, making it suitable for structural applications (Awoyera and Adeyinka, 2018). Additionally, Opepe is abundant and locally available in Nigeria, reducing the need for imported materials and supporting the local economy. According to the Nigerian Institute of Architects (NIA), Nigeria has a significant housing deficit, with an estimated shortage of over 17 million housing units (Olubunmi and Ibrahim, 2019). Most of the existing housing structures in Nigeria are made of reinforced concrete, which is costly, time-consuming to construct, and has a high carbon footprint (Kolawole and Akinmusuru, 2020). This has led to an increased interest in alternative building materials, such as light-frame timber using Opepe, which can provide a sustainable and cost-effective solution to the housing deficit in Nigeria.

One of the main benefits of using light-frame timber is its environmental sustainability. The production of timber has a lower carbon footprint compared to reinforced concrete, as timber stores carbon during its growth and has a lower embodied energy than concrete (Ali *et al.*, 2019). A study by the Food and Agriculture Organization (FAO) of the United Nations found that sustainable forestry management practices can contribute to climate change mitigation and adaptation, and can reduce deforestation rates (FAO, 2015). In addition to its environmental benefits, light-frame timber offers several advantages over reinforced concrete in terms of cost and construction time.

A study by the American Wood Council (AWC) found that light-frame timber construction can reduce construction time by up to 25% compared to traditional construction methods (AWC, 2019). Furthermore, the use of local materials, such as Opepe, can reduce the cost of construction by up to 20% compared to imported materials (Kolawole and Akinmusuru, 2020). However, there are also challenges and limitations associated with the use of light-frame timber in general in low-rise residential construction in Nigeria. These include issues related to fire safety, durability, and pest control. For example, termites and other pests can cause significant damage to timber structures if not properly treated (Awoyera and Adeyinka, 2018). Additionally, the use of timber in construction requires appropriate fire safety measures to ensure the safety of occupants and prevent fire spread (Ali *et al.*, 2019). Several researches were conducted in this regards. For instance Filiatrault (1990) developed and validates a simple structural analysis model to predict the behaviour of timber shear walls under lateral static loads and earthquake excitations. More recently, simple formulae have been used to determine an appropriate FRR given the ventilation parameters of a compartment, the likely fuel load and to a lesser extent the thermal properties of the compartment boundaries. (Thomas, 1997) determine the validity of these formulae for light timber frame walls and floors and other materials. The aim of (Robertson *et al.*, 2012) was to quantify and compare the environmental

impacts associated with alternative designs for a typical North American mid-rise office building. A consequential-based lifecycle approach is used here to explore the carbon implications of conventional and low-energy versions of three timber multi-storey building systems (Dodoo *et al.*, 2014). (D'Ambrisi *et al.*, 2014) study experimental investigation on flexural behavior of timber beams repaired with cfrp plates. An experimental investigation on timber beams repaired and strengthened with carbon fiber reinforced polymer (CFRP) plates is presented. The extent to which different climate scenarios influence overheating risk, energy use and peak loads for space conditioning of district heated multi-storey buildings in Sweden are explored (Dodoo *et al.*, 2016). An output-only modal analysis method was used to identify the modal properties of the buildings: the random decrement technique was applied to the stochastic measured response, and then the time-domain random decrement signature was used for modal analysis by the Ibrahim Time Domain method (Reynolds *et al.*, 2016). (Balasbanch *et al.*, 2018) study sustainability choice of different hybrid timber structure for low medium cost single-story residential building: environmental, economic and social assessment. The impact of different hybrid timber building construction on three different categories namely: environment, economic and social is analyzed. Other influential work includes Poletti *et al.*, (2014).

This paper aims to investigate the feasibility of using light-frame timber with Opepe as a replacement for reinforced concrete in low-rise residential houses in Nigeria. Consequently, the findings of this study will provide insights into the feasibility, benefits, and challenges of using light-frame timber with Opepe in low-rise residential construction in Nigeria. This research will contribute to the development of sustainable and eco-friendly housing solutions in Nigeria, which is crucial for addressing the housing deficit in the country.

Research Methodology

The material used for the light-frame timber analysis and design was Opepe (Nauclea diderrichi), a large African forest tree that yields a strong, hard yellow to golden brown lumber. It belongs to the Rubiaceae family, it is highly stable with a strong resistance to impact, negligible shrinkage, medium bending, crushing strengths, stiffness and a very substantial hardness. All of these aforementioned qualities make it a very good option for Civil Engineering construction and structural works. The Opepe timber belongs to the hardwood specie and is graded D50 in strength class according to the EN 338 and has the following properties according to service class:

Table 1: Strength Classes and Characteristic Values According to EN 338.

	Deciduous specie	
	D50	
Strength properties in N/mm ²		
Bending	$f_{m,k}$	50
Tension parallel to grain	$f_{t,0,k}$	30
Tension perpendicular to grain	$f_{t,90,k}$	0.6

Compression parallel to grain	$f_{c,0,k}$	29
Compression perpendicular to grain	$f_{c,90,k}$	9.7
Shear	$f_{v,k}$	4.6
Stiffness properties in kN/mm ²		
Mean value of modulus of elasticity parallel to grain	$E_{0,mean}$	14
5% value of modulus of elasticity parallel to grain	$E_{0,05}$	11.8
Mean value of modulus of elasticity perpendicular to grain	$E_{90,mean}$	0.93
Mean value of shear modulus	G_{mean}	0.88
Density in kg/m ³		
Density	ρ_k	650
Mean value of density	ρ_{mean}	780

Design Software

The Software adopted for the design and analysis was Tekla Structural Designer 18 and also Autodesk Robot 18. The TSD 18 software was only used to develop the 3D visualization (After modelling the structure, it was discovered that the versions of TSD available as at the time of this research couldn't design for timber sections). Autodesk Robot was eventually used for the complete analysis and design.

Structural System

Light-frame system of timber construction is characterized by continuous arrangements of sawn lumbers (studs and joist) of small sizes, closely-spaced and in parallel positions from each other, the typical intervals vary from 16-24 inches apart. It has structural panels spanning across the lumber members forming walls and floors. Being "light" as the name implies, the method of structural configuration limits floor spans to 8-10m, and height limit using the light-frame technology is currently 6-7 storeys.

Structural Model

To analyze the structural use of the Opepe hardwood timber for low-rise residential houses, the structural G.A for a 5000sq.m, residential duplex was developed. The G.A consists of a foundation layout: a number of shallow, reinforced concrete pad footings (600mm², 450mm depth), 8 x 8 inch, 750mm deep timber posts connected to the footings by CPTZ (zinc plated Simpson post tie), on 25mm, post bases in form of seal plates all anchored to the reinforced concrete footings using HD bolts with sufficient load carrying capacity, 4 x 8 inch hanger joists are then connected to the timber foundation studs, 3 x 6 inch trimmer joists are connected to the hanger joists which in turn supports the floor decks. Considering the light-frame structural system, standard construction practice specifies the wall studs to be 2 x 4 inch in minimum

dimension, and at 600mm spacing from each other. All structural components are being predrilled (being hardwood) at appropriately calculated distances in preparation for the nailing connections.

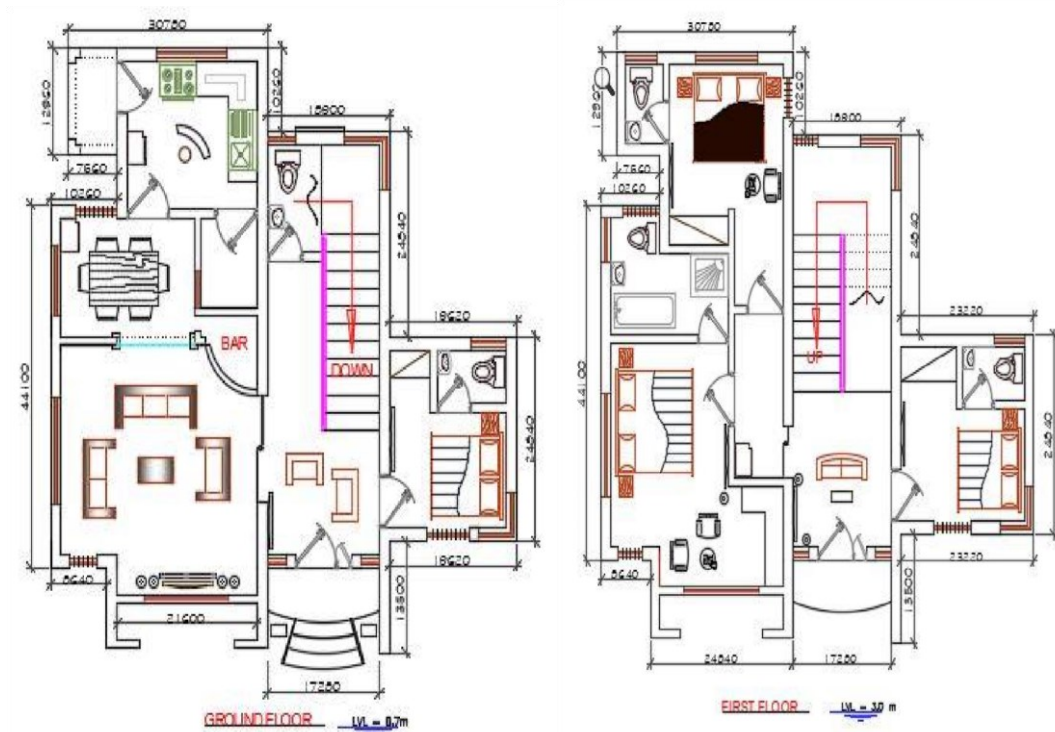


Figure 1a: GroundFloor Plan of a one storey building **Figure 1b:** FirstFloor Plan of a one storey building

General Arrangements for the Light-frame structure are as follows:

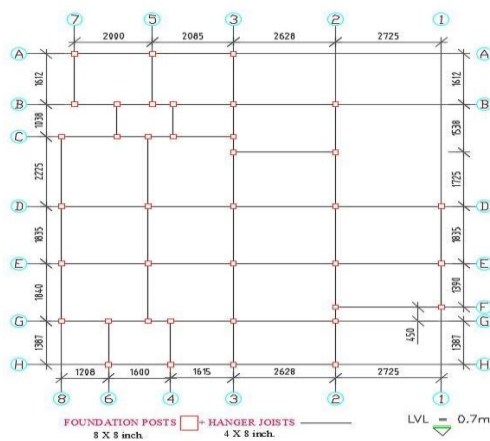


Figure 2: Foundation Posts and Hanger Joists G.A

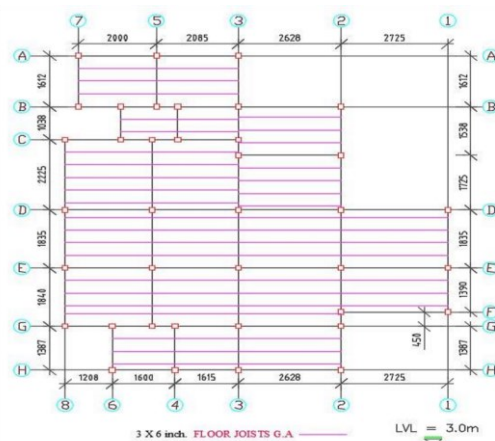


Figure 3 Floor Joists G.A

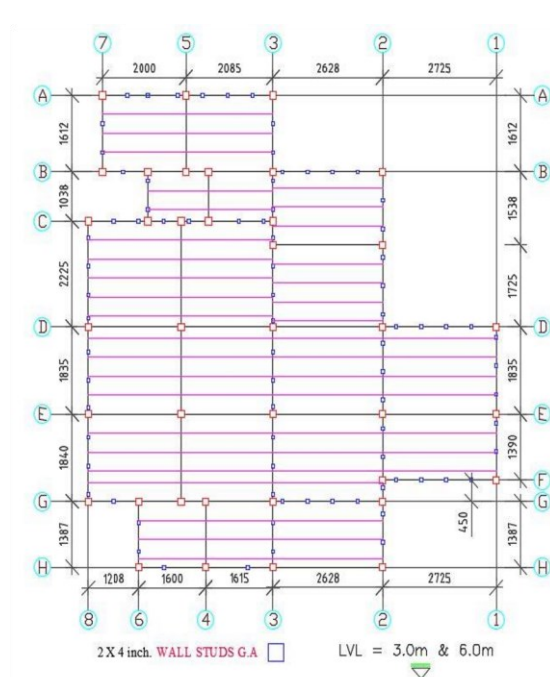


Figure 4: Wall Studs G.A

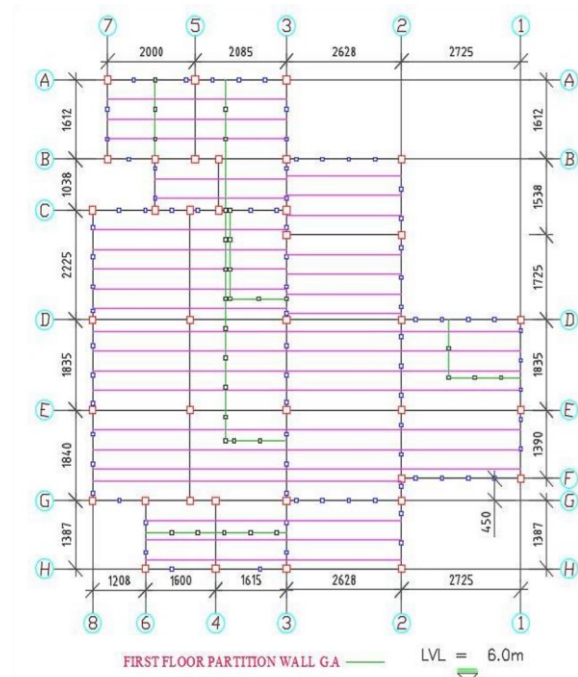


Figure 5: First Floor Partition Wall G.A

3D Visualization

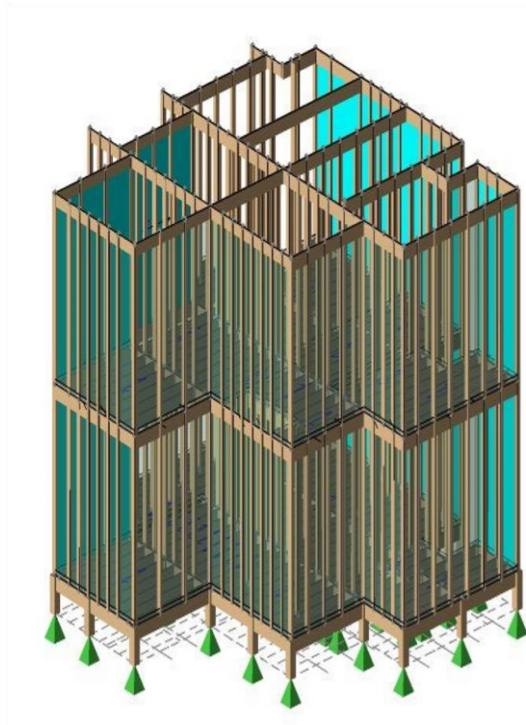


Figure 6: TSD3D representation



Figure 7: AutodeskRobot3D representation

Analysis and Design

The principal method of designing timber-framed structures has dominantly been allowable stress design (ASD). In this paper, the most up-to-date version of ASD method (AF and PA, 1997) was adopted. It should be noted that the load resistance factored design method (LRFD) was also now allowable as an alternative method. The ASD method is well elaborated in the National Design Specification for Wood Construction (NDS).

Loading

Asides from some few factors (load sharing, load duration and certain adjustment factors), loading on timber structures and its members are the same as those for components of other materials (concrete and steel). These categories of loads are stated below, refer to BS EN 19911-1:2002 for their governing conditions and detailed values.

- i. Self-weight of the structural members
- ii. Other permanent loads such as finishes, walls, and partitions, etc.
- iii. Imposed loading such as stored materials
- iv. Imposed loading such as occupants of the structure
- v. Imposed loading such as snow on roofs (not applicable in this paper, instead we use "L_r" which is the maximum roof live load anticipated from construction/maintenance)
- vi. Wind loading, either vertical, horizontal, inclined, external, internal pressure or suction and drag.

Load Duration Factor (CD)

It's important to note that Timber has the property of being able to withstand higher stresses for short periods of time than those it can withstand for longer periods or permanently. Hence, load duration is a determining factor in the design procedure and are stated below based on NDS 2.3.2 and NDS appendix B (AF & PA. 1997.)

Table 2: Recommended Load Duration Factors (CD)

Normal	Ten years	1.0
Occupancy (Live Load)	Seven days to ten years	1.0 – 1.5
Snow	Seven days to one month	1.15 – 1.25
Temporary construction	Seven days	1.25
Wind and seismic	One minute to minutes	1.6 to 1.8
Impact	One second	2.0
Permanent (Dead Load)	Lifetime	0.9

Load Combination

It's imperative for the structural engineer to first determine the different loads acting on the structure and its various elements before proceeding to the design. Load combinations used in the case of light-frame timber system according to the ASD method are listed below:

Table 3: Load Combinations

Component or System	ASD Load Combination
Foundationwall	$D + H$
(gravity and soil lateral loads)	$D + H + L + 0.3(Lr + S)$
Headers, girders, joists, interior bearing walls and	$D + H + (Lr \text{ or } S) + 0.3L$
columns, footings (gravity loads)	$D + (Lr \text{ or } S) + 0.3L$
Exterior load-bearing walls and columns (gravity and transverse lateral loads)	$D + W$
	$D + 0.7E + 0.5L + 0.2S$
	$D + (Lr \text{ or } S)$
Roof rafters, trusses, and beams, roof and wall sheathing (gravity and wind loads)	$0.6D + Wu$
	$D + W$
Floor diaphragms and shear walls (in-plane lateral and	$6D + (W \text{ or } 0.7 E)$
overturning loads)	0.

Where:

D = estimated mean dead weight of the construction.

H = design lateral pressure for soil condition type.

L = design floor live load.

Lr = maximum roof live load from construction and maintenance.

W = design wind load.

S = design roof snow load.

E = design earthquake load.

Note: For load combinations for timber structures in regions like Nigeria where there is absence of snow,

L_r is substituted for snow load during analysis and design calculations

Structural Checks

The principal method of designing wood-framed structures is the allowable stress design (ASD), and also load resistance factored design method (LRFD). The structural evaluation for timber frame analysis was accomplished by these structural safety checks:

- i. Bending capacity
- ii. Horizontal shear
- iii. Combined bending and axial bending
- iv. Compression and column stability
- v. Tension

Design Procedures (Using Autodesk Robot Structural Designer 18)

- i. Using the developed general arrangements, the light-frame structure was modelled by selecting initial trial sections for foundation posts, hanger joists, trimmer joists and wall studs.
- ii. Load types were selected as thus:
 - a. Dead Load (DL1): Structural
 - b. Live Load (LL1): Category A
 - c. Wind Load.
- iii. The Live Load (1.5KN/m^2) was defined to be "Surface Uniform Planar Load" and then added to the timber decks.
- iv. The Load Combination was generated in Ultimate Limit State (ULS), which included all the load cases initially defined: ($1.35\text{ }DL1 + 1.5\text{ }LL1 + 1.5\text{ }WL1$.) and was stated as "COMB 1".
- v. The wind load simulation was run by imputing the wind parameter which in this case is the average wind velocity in Nigeria, which ranges from $2 - 9.5\text{m/s}$. The wind directions considered were $+X$, $-Y$, $-X$, and $+Y$.
- vi. The analysis was then carried out using the "calculation" icon on the software, to get the reactions on the foundation footings, shear forces, bending moments and the deformation values.
- vii. Timber member design options were set to "ULS COMB1", which is the governing load case. And also under configuration, for load case classification of Timber Design according to duration, the "permanent" option was selected.

- viii. The structure was then designed for members' verification, and higher sections were reselected in cases of inadequate section sizes.

It was noted that although the load combination option during the design phase was selected to be in Ultimate Limit State (ULS), but the software makes use of Allowable Stress Design (ASD) during the timber members verification calculations as shown in the resulting calculation notes.

Result and Discussion

Analysis Results and Section Selection

The results from the analysis showed the values for axial forces (reactions) through the foundation studs on the foundation supports, the shear forces, and bending stresses, which are section characteristics that govern the allowable stresses for each section size and shape. Below, are pictures that show these results as presented by the design software.

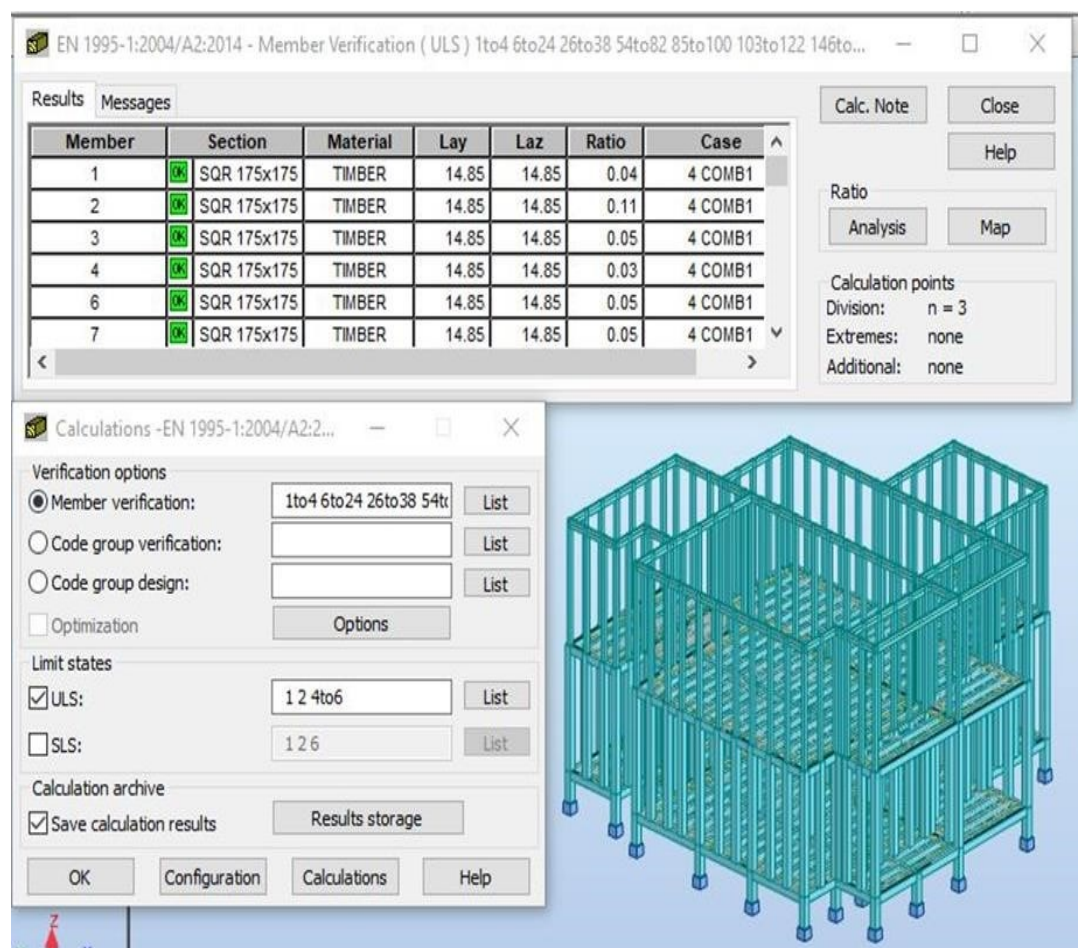


Figure 8: Members Verification Calculation

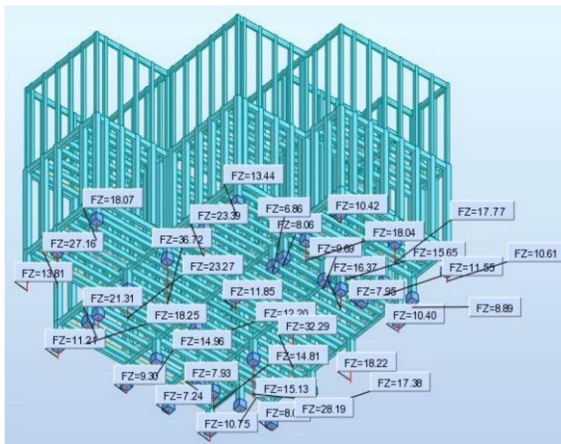


Figure 9: Axial Forces at supports

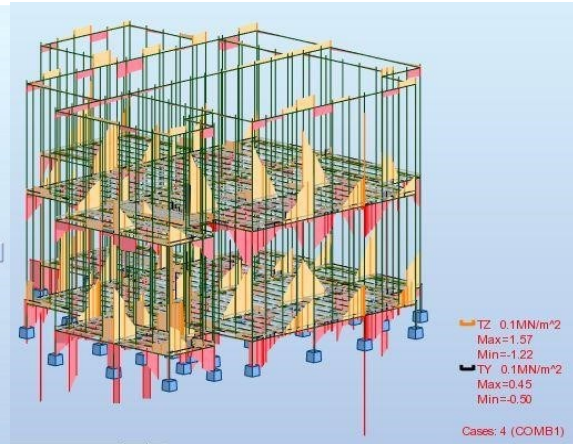


Figure 10: Shear Forces along Y and Z directions

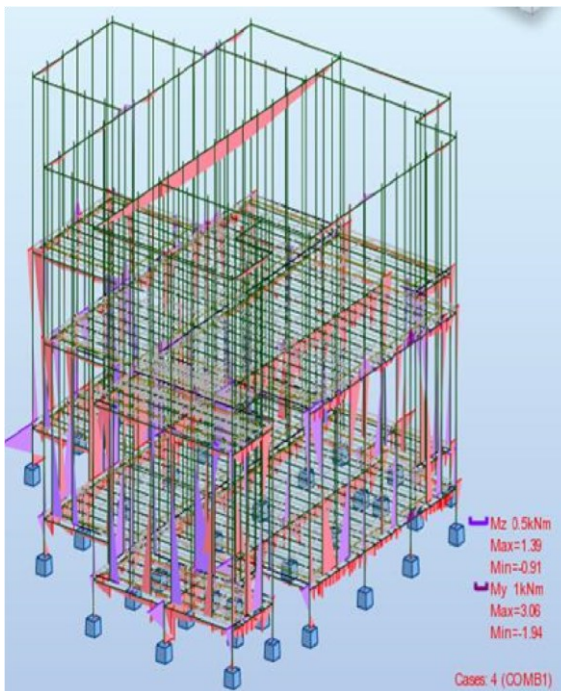


Figure 11: Bending Moments along Y and Z directions

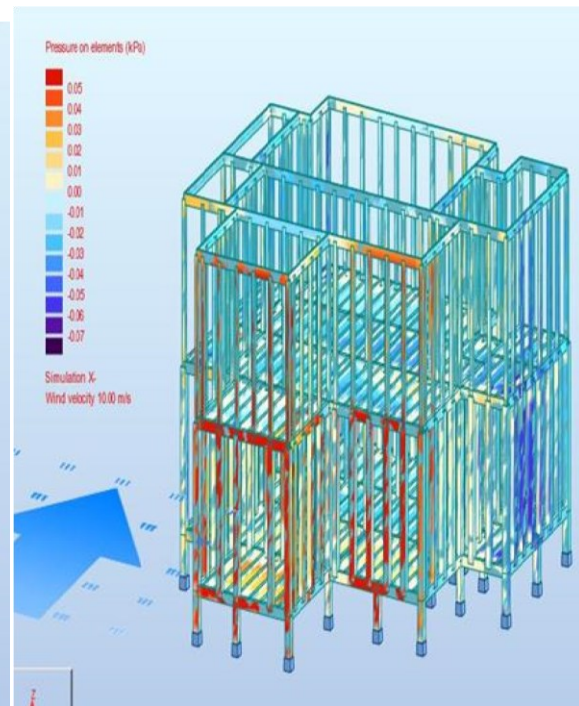


Figure 12: Wind Load Simulation at 10m/s

Section Selection

In the course of the analysis, initial trial sections of foundation studs, hanger joists, trimmer joists, ground and first floor studs, primary and secondary beams, as well as roof beams were selected. After the calculation phase, wind load simulation and members verification, some of the trial sections failed for having ratios between normal and allowable stress ($\tau_z, d/Kcr + \tau_{torz}, d/Kshape)/fv, d$ less than 1. Deck thickness of 25mm was constant for all floors. The initial trial and final sections are shown below:

Table 4: Initial Trial Sections

Structural Members	Initial Trial Sections
Foundation studs	SQR 200mm X 200mm
Ground floor studs	SQR 75mm X 150mm
Hanger joists	BALK 100mm X 150mm
Trimmer joists	BALK 50mm X 150mm
First floor studs	SQR 100mm X 100mm
Primary beams	BALK 100mm X 150mm
Secondary beams	BALK 75mm X 100mm
Roof beams	50mm X 150mm

Table 5: Final Design Sections

Structural Members	Initial Trial Sections
Foundation studs	SQR 175mm X 175mm
Ground floor studs	SQR 75mm X 150mm
Hanger joists	BALK 100mm X 200mm
Trimmer joists	BALK 75mm X 175mm
First floor studs	SQR 100mm X 100mm
Primary beams	BALK 100mm X 200mm
Secondary beams	BALK 75mm X 175mm
Roof beams	50mm X 200mm

Conclusion

At the end of the research, unlike the commonly associated wood specie (soft wood) with lightframe timber structures, the use of Opepe hardwood (readily available locally) graded D50 by the Eurocode and has shown tremendous strength characteristics higher than any soft wood. Analysis results of members' verification also showed that Opepe on the average, depending on load values and structural configuration, has a very low Delta value, which is the ratio between normal and allowable stress (the governing structural check for allowable stress design).

It is understandable how questions on timber connections design, racking and fire resistance, construction methodologies and best practice, as well as local standardization of structural timber can come up in the course of venturing deeply into timber engineering, and while this research work is partly intended to provoke these questions in the Civil Engineering industry in Nigeria, It is therefore recommended that structural Engineers in this part of the world should

start looking at various emerging materials (composite or not) in built environment as it will contribute significantly into achieving the world's net zero emission by 2050.

References

- Ali, M., Memon, S. A. & Raza, S. (2019). An overview of cross-laminated timber: Advantages, challenges and prospects. *Construction and Building Materials*, 224, 812820. doi: 10.1016/j.conbuildmat.2019.07.031
- Awoyera, P. O. & Adeyinka, A. A. (2018). Evaluation of the mechanical properties of Opepe wood. *Journal of Materials Research and Technology*, 7(4), 488-495. doi: 10.1016/j.jmrt.2018.01.010
- Berardi, U. & Ghaffarianhoseini, A. (2019). Timber as a sustainable building material: A review of recent research. *Sustainability*, 11(12), 3337. doi: 10.3390/su11123337
- FAO. (2021). *Global Forest Resources Assessment 2020. Country Report: Nigeria*. Retrieved from <http://www.fao.org/3/cb4273en/cb4273en.pdf>
- Kolawole, O. A. & Akinmusuru, J. O. (2020). An appraisal of cost variation order factors in Nigerian construction industry. *Journal of Construction in Developing Countries*, 25(1), 49-66. doi: 10.21315/jcdc2020.25.1.4
- Olubunmi, A. O. & Ibrahim, O. A. (2019). Sustainable housing delivery: An empirical study of housing finance and building materials in Nigeria. *Journal of Sustainable Development*, 12(2), 80-90. doi: 10.5539/jsd.v12n2p80
- Ozor, P. & Onwuka, D. O. (2020). Materials and methods for sustainable building construction in Africa: A review. *Journal of Building Engineering*, 29, 101089. doi: 10.1016/j.jobe.2020.101089
- Filiatrault A. (1990). Static and Dynamic Analysis of Timber Shear Walls. *Canadian Journal of Civil Engineering*, 17(4), 643-650. <https://doi.org/10.1139/I90-073>
- Thomas, G. C. (1997). *Fire Resistance of Light Timbered Frames Walls and Floors*. Masters Thesis, University of Canterbury. Department of Civil and Natural Resources Engineering
- Robertson, A. B., Lam, F. & Cole, R. J. (2012). A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete. *Buildings*, 2(4), 245-270. doi: 10.3390/buildings2030245
- Dodoo, A., Gustavsson, L., & Sathre, R. (2014). Lifecycle Carbon Implications of Conventional and Low-energy Multi-storey Timber Building Systems. *Energy and Buildings*, 82, 194-210. doi: 10.1016/j.enbuild.2014.06.034
- D'Ambrisi, A., Focacci, F., & Luciano, R. (2014). Experimental Investigation on Flexural Behavior of Timber Beams Repaired with CFRP Plates. *Composites Structures*, 108, 720-728. Doi: 10.1016/j.compstruct.2013.10.005
- Poletti, E. & Vasconcelos, G. (2014). Seismic Behaviour of Traditional Timber Frame Walls: Experimental Results on Unreinforced Walls. *Bulletin of Earthquake Engineering*, 13(3), doi: [10.1007/s10518-014-9650-9](https://doi.org/10.1007/s10518-014-9650-9)
- Dodoo, A. & Gustavsson, L. (2016). Energy Use and Overheating Risk of Swedish Multistorey Residential Buildings Under Different Climate Scenarios. *Proceedings of ICE - Energy*, 97, 534-548. DOI: 10.1016/j.energy.2015.12.086

Reynolds, T., Casagrande, D., & Tomasi, R. (2016). Comparison of Multi-storey Crosslaminated Timber and Timber Frame Buildings By in Situ Modal Analysis. *Construction and Building Materials*, 102. DOI: [10.1016/j.conbuildmat.2015.09.056](https://doi.org/10.1016/j.conbuildmat.2015.09.056)

Balasbaneh, A. T., Marsono, A., & Khaleghi, S. J. (2018). Sustainability Choice of Different Hybrid Timber Structure for Low Medium Cost Single-story Residential Building:

Environmental, Economic and Social Assessment. *Journal of Building Engineering*, 20, 235-247. Doi: [10.1016/j.jobbe.2018.07.006](https://doi.org/10.1016/j.jobbe.2018.07.006)