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Design, Analysis and Performance Evaluation of a Standing Wooden Shelf Using Glued-Laminated Panels

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Abstract

The desire to accord furniture its place as a structural entity, has brought emphasis to the theoretical aspect of its design. This research aims at analysing the performance of a wooden shelf in theory and practical situation. The standing wooden shelf was developed using AutoCAD inventor 2017 and structurally analysed. The shelf consists of four columns, five glued-laminated cantilever panels attached to the column and a base. The loads, bending stress, shear and deflection criterion were computed. The prototype of the designed furniture was fabricated and loaded to examine it performance. The practical performance evaluation showed that the shelf was able to carry and transmit a maximum load of 52.272kg (512N), with 7.502kg(73N), 10.049kg (98N), 13.291kg (130N), 8.97kg (87), 7.098kg (69N) and 5.362kg (52N) at loading points A, B, C, D, E and F respectively. This compared to the design load capacity was beyond adequate and without failure. This study supplies background information in the design and load bearing capacity of a glued-laminated wooden shelf. It is recommended that the use of Computer Aided Design (CAD) software such as SOLIDWORKS, ANSYS be explored in the design and analysis of furniture.

Keywords: Furniture, Structure, Design, Analysis,Evaluation, Glue-laminate, Wooden, Shelf

1. Introduction

Furniture is an inevitable item to human existence as can be seen from history (Eckelman, 2003). It has been part of life before the pre-historic era, most of which are evident in paintings and recent excavations dated back to the Neolithic Period (Smardzewski, 2015). In Nigeria, the furniture industries date back to 1872 when commercial logging commenced in the country (Adewole and Bello, 2013; Ogunwusi and Olife 2012). In spite of the long history of furniture, it is seldom considered as a structural component hence the engineering design aspect is often ignored (Adewole and Olorunnisola, 2010). Many reasons account for this but the basics are that the safety limit of furniture is usually not exceeded and injuries obtained in failure are usually minimal compared with other structures (Eckelman, 2003). The common practice in the manufacturing of furniture is what Adewole and Olorunnisola (2010) referred to as the copy and paste trial by error method, where one size and standard is used to produce for all using catalogues. This process gives room for wastage of material without guarantee of safety or assurance that the furniture will serve its design purpose (Adewole and Isedowo, 2012). With adequate consideration of furniture as a structural component, wastage and cost can be moderated.

Furniture engineering design can be defined as the development of a product using scientific means and methods under the sway of certain physical and mechanical guidelines and controls (Eckelman, 2003). The primary goal of engineered construction is to develop a structure that optimally combines safety, economy, function and aesthetics (Aguwa, 2012). The design of furniture as a structural component has become a necessity due to the need to manage materials and attain a better means of certifying the strength of the product (Erdil, 2004). In the design process of furniture, four basic aspects must be given consideration, the structural integrity, ergonomic satisfaction, aesthetics and cost (Adewole, and Isedowo, 2012). Although, the aesthetic value of a piece of furniture is always held in high priority, the structural integrity of the furniture determines how long the furniture will stay in use (Eckelman *et al.*, 2003).

In comparing the structural analysis of furniture strength to that of buildings, machines, and its other counterparts, the concept of furniture design in relatively new. Furniture had not been investigated structurally until the mid-1950s (Erdil *et al.*, 2004). As stated by Eckelman (1968) and asserted by Erdil *et al.* (2004) "The manual processes of analysing most pre-existing furniture were so rigorous and manually tasking. Oftentimes, they were statically indeterminate (their members were often curved and of non-constant cross section making the use of formula impossible). These factors complicate the execution of analysis. Since engineering design includes an analysis of the behaviour of individual fasteners and joints in the structure." However, when components of furniture are strait and regular, members can easily be analysed using different design methods. A simplified analytical method was developed by Dai and Zhang (2008, which used beam models to analyse and calculate bending moments of critical structural members in a three-dimensional sofa frame. With the current advent of computer programmes for structural analysis, furniture design had been made which help in simplifying the design process.

For a furniture to be adequately and structurally analysed, the load and forces acting on the components must first be determined. Eckelman (2003) had tabulated data for different furniture with different loading conditions. Aside knowing and determining the load that will act on the structure when in service, other components involved in the design process includes; estimating the dimensions of timber structure and analysing the magnitude and distribution of the forces which arise in trial structure under action of the external loads (Eckelman 2003).

These are the same principles used for analysing beams and columns in timber structures and can be applicable in design of furniture as a structural component (Olorunnisola, 2018). This work adopted the idea of Eckelman (2003) on the need to subject furniture design to mathematical analyses in order to reduce cost and produce efficient furniture.

2.0 Methodology

2.1 Design, Analysis and considerations

The standing book shelf was designed, using AutoCAD inventor 2017 (Figure 1). It comprises of four columns (two major and two minor) joined together at the top and lower ends. The two major column bearing eccentric load at one side of the column while the minor columns act as support and are eccentric loaded at one side. A cantilever laminated panel attached to the sides of the column carries the load of the structure. The beams are attached to the columns using mechanical fasteners (Nails) and designed as cantilever beams. Structurally analysed using detailed analytical procedures are presented in the study below.

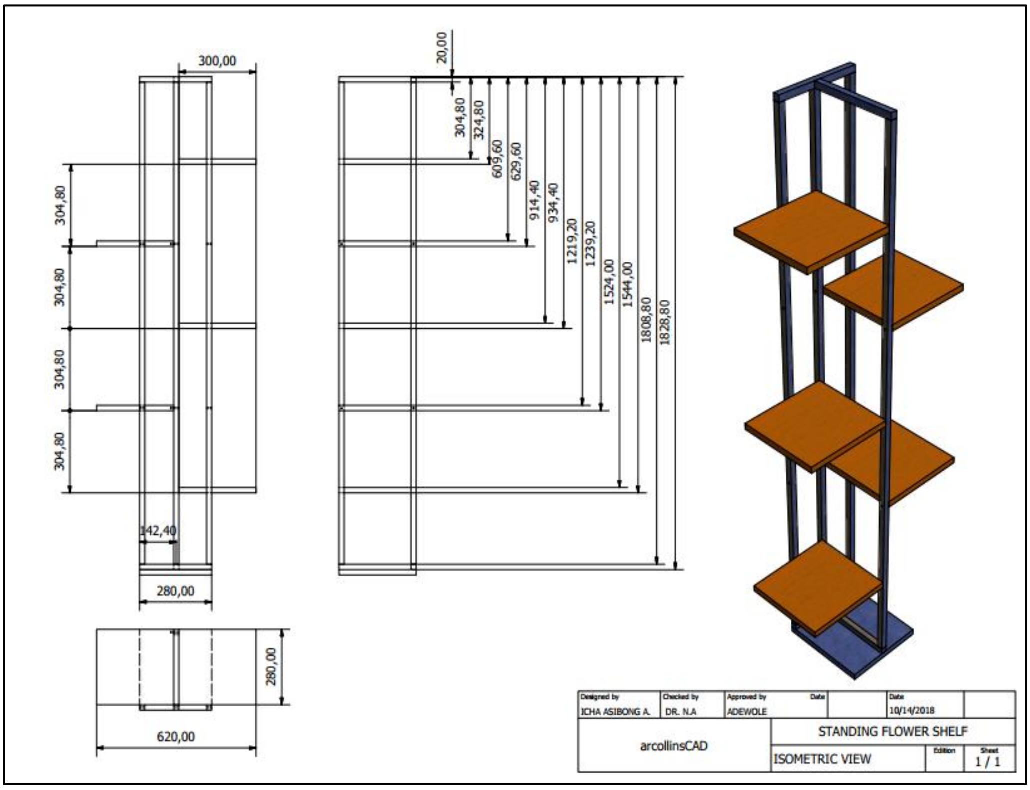

Figure 1. Detailed Drawing of Glued-Laminated Book Shelf

Glued Laminated Panels with three mixed species of *Funtumia africana*, *Khaya grandifoliola*, *Celtis mildbraedi*recovered from construction site was use (Adewole and Icha, 2021). Design procedure in accordance with ASTM D3737 (2006) was applied. Figure 2 shows the grade combination with the different species of laminating lumber throughout the width of the transformed section. The Modulus of Elasticity (MOE), moment of inertia, section modulus, and bending stress of the transformed glued-lam was computed using methods from Ozelton and Baird, (1981), Williams and Yeh (2007) and Moody, (1974). Moody, and Hernandez

(1977).(equation 1-6). The loads to which the furniture (shelfs) is to be subjected was determined using tabulated data in accordance with Eckelman (2003) and density of the transformed section for live and dead loads respectively. A factor of safety was added to load and summed up to the total load.

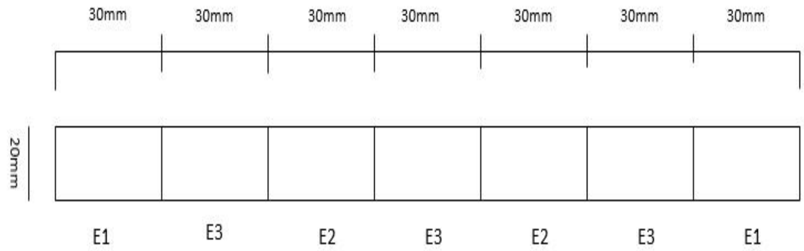

Figure 2. Different grade combination intermixed

a) Average MOE

The Average MOE is calculated using

$MOE_N =$
MOE_I ……………………………… (1)

b) Moment of Inertia

The transformed moment of inertia for each lamination was calculated using

$I_j = b\left(\frac{E_j}{E_T}\right)$ ………………………….
(2)

Where: I_j = transformed moment of inertia of jth lamination, E_j = modulus of elasticity of the jth lamination, E_T = modulus of elasticity of the transformed lamination, b = un-transformed width of lamination

The moment of inertia for transformed width is calculated using

$I_T = \sum_{j=I}^{nI} I_j$ ………………….. (3)

The moment of inertia of the transformed section is calculated using

$I_g = \frac{Bd^3}{12}$……………… (4)

Where: I_g = the gross moment of inertia of the section, B = the transformed width of the section, d = the depth of lamination

c) Section Modulus

The section modulus is calculated using

$S_g = \frac{Bd^2}{6}$ ……………… (5)

Where: S_g = the gross section modulus, B = the transformed width of the section, d = the depth of lamination9460mm^3

d) Design Bending Stress

To determine the allowable bending stress (F_{by}) for the glulam member loaded on the Y-Y axis (vertically), F_b is equal to 1.15 times the weighted average of the corresponding design stresses of the various component laminations.

The allowable bending stress is calculated using

$F_b = 1.15[f_{b1}\left(\frac{2}{7}\right) + f_{b2}\left(\frac{2}{7}\right) + f_{b3}\left(\frac{3}{7}\right)]$ ……………….. (6)

The prototype of the designed furniture was fabricated and subjected to practical

2.2 Performance testing

testing using an electric weighing machine with capacity of 100kg and book as the load. The initial weight of the furniture was recorded and the weight after loading at different loading points A – F. The total

2.3 Design Calculations of Standing Book shelf

2.3.1 The cantilever panel

The cantilever panel of the standing book shelf acts like a beam fixed at one end and free at the other end supporting a uniformly distributed load. It is assumed that the structure is expose to static live load (weight of books) and death load (weight of laminated panel) only.

To determine the total load exerted on each beam,

V = l x b x h = 300 x 200 x 20 = 1200000mm^3

$D = \frac{M}{V}$; ……………………….(7)

Using the density of the transformed section,

D = 570.5 which is the highest density amongst the three species.

M = 570.5 x 0.012 = 0.6846kg

Weight = 0.684 x 9.81 = 6.71N

Factor of safety for dead load = 1.4

Weight = Density x factor of safety

= 6.71 x 1.4 = 9.40N

Converting dead load to Uniformly distributed load $= \frac{9.40}{200\ x300} =$ 0.00156N/mm^2

Live load = 0.002394 x 1.6 = 0.003830

Total load = 0.003830 + 0.000156 = 0.003990N/mm^2

Bending Criterion

$\frac{M}{S} \leq f_b$ ……………………………….(8)

weight of the furniture was also recorded. Care was taken to make sure the readings were accurate.

$M = -\frac{wl^2}{2} = -\frac{0.0053990 \text{ x } 300^2}{2} = -\frac{359.1}{2} = -$ 179.37N

S = 9460mm^3 $= \frac{179.37}{9460} \leq 57.97 = 0.01896 \leq$ 57.97

Therefore, the design is **SAFE**

Shear Criterion

τ_{max} (fv) $\leq \tau_{allowable}$ (Fv) ……………… ………. (9)

$\tau_{max} = \frac{3V}{2bd} \leq 1.86$ ……………………… (10)

V = wl = 0.003990 x 300 = 1.197

$= \frac{3\ x\ 1.197}{2x200x20} = \frac{3.591}{8000} \leq 1.86 = 0.0004488 \leq$ 1.86

Therefore, the design is **SAFE**

Deflection Criterion

$$actual\ deflection \leq allowable\ deflection$$

$actual\ deflection = \frac{wl^4}{8EI}$ ……………… ………. (11)

$allowable\ deflection = \frac{L}{240}$ …………… ………… (12)

Where

w= uniformly distributed load in N/mm^2;l = span of the beam;E= modulus of elasticity of wood specie = 9,200 N/mm^2;I = moment of inertia in mm^4;

$= \frac{wl^4}{8EI} = \frac{0.003990\ x\ 300^4}{8\ x\ 9200\ x\ 94600} = \frac{32319000}{6962560000} =$ 0.0046mm

$\frac{L}{240} = \frac{300}{240} = 1.25$mm

0.0046mm ≤ 1.25mm

Therefore, the design is **SAFE**

2.3.2The Column

The column was designed as a beam carrying point loads to determine the maximum bending moment and analysed as a combined beam column to find the safe load (Figure 3 and 4).

RA + RB = 0.00399 x 5

RA + RB = 0.01995

Taking moment at point A

RB x 180 = 0.00399 x 30 + 0.00399 x 60 + 0.00399 x 90 + 0.00399 x 120 + 0.00399 x 150

180 RB = 0.1197 + 0.2394 + 0.3591 + 0.4788 + 0.5985

180 RB = 1.7955

RB = $\frac{1.7955}{180}$ = 0.009975

RA + RB = 0.1995

RA + 0.009975 = 0.1995

RA = 0.1995 – 0.009975 = 0.189525

Bending Moment Calculation

At point 1, BM = 0

At point 2, BM = RA x 30 = 0.009975 x 30 = 0.2996

At point 3, BM = RB x 60 – 0.00399 x 30 = 0.009975 x 60 – 0.1197 = 0.4788

At point 4, BM = RB x 90 – (0.00399 x 60 + 0.00399 x 30) = 0.53865

At point 5, BM = RB x 120 – (0.00399 x 90 + 0.00399 x 60 + 0.00399 x 30) = 0.4788

At point 6, BM = RB + 150 – (0.00399 x 120 + 0.00399 x 90 + 0.00399 x 60 + 0.00399 x 30) = 0.29925

At point 7, BM = 0

Maximum bending moment = 0.5387

The interaction equation used to represent the combined conditions assuming concentric end loads plus side loads is shown in equation (13)

$$\frac{P/A}{F'_C} + \frac{M/S}{F_b - P/A} \leq 1.0 \text{ .... (13)}$$

Section Modulus, S = $\frac{bd^2}{6} = \frac{20 \, x \, 40^2}{6}$ = 5333.33

Assuming total load, P = 239.24N

Area = 20 x 40 = 800

$$\frac{239.24/800}{0.3306} + \frac{0.5387/5333.33}{51.39 - 239.24/800} \leq 1.0$$

$$\frac{0.29905}{0.3306} + \frac{0.000101006}{51.39 - 0.29905} \leq 1.0$$

$$0.90457 + 0.000001977 \leq 1.0$$

0.9046 < 1.0

Column is **ADEQUATE**

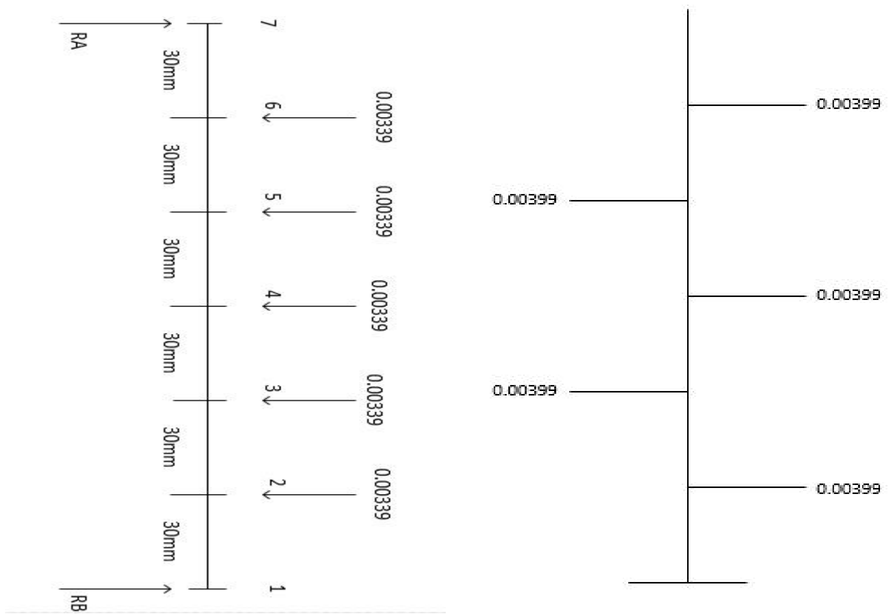

Figure 3. Loading and Actual Load Distribution Diagram for Combined Beam Column.

3.0 Results and Discussion

3.1 Performance testing of Bookshelf

Table 1 presents the weight of the book shelf before and after loading at points A – F. The final weight exacted at each point is also present on the table. The weight of the bookshelf before loading at point A starts from 8.78kg and ends at 55.69kg (point F). while the bookshelf after loading at point A and ending at point F, starts at 16.29kg and ends at 64.06kg respectively. The load value from point A – F, is recorded as 52.272kg (512N), with 7.502kg (73N), 10.049kg (98N), 13.291kg (130N), 8.97kg (87), 7.098kg (69N) and 5.362kg (52N) respectively. It can be observed from the table that the initial value of the load at point A did not generate from Zero (0), this is due to the weight of the bookshelf which weighs 8.78kg (86N), an average of the sum load value of the bookshelf.

Table 1. Result of Performance Testing of Glued-Laminated Bookshelf

Load Points	Weight of Furniture before Loading (Kg)	Weight of Furniture after Loading (kg)	Final Weight of the Load (kg)
A	8.789	16.291	7.502
B	16.291	26.34	10.049
C	26.34	39.631	13.291
D	39.631	48.601	8.97
E	48.601	55.699	7.098
F	55.699	61.061	5.362
Sum			**52.272**

Figure 4 is a graphic representation of the load distribution on the bookshelf. It also shows the progressive loading process with time. It was observed that the load was highest at load point C with a point load of 13.291kg (130N). This is due to the unequal distribution of loading points on the bookshelf. The lowest point of loading is at point F with 5.362kg (52N). this can also be attributed to the uneven load points with the right side have more load point (3) than the left hand side of the shelf (Plate 1a) allowing for balancing and stability. Plate 1(a-e) shows the bookshelf during loading. It is also observed that the base could not take more loaddue to the height limitation of the baseat point B. other observations include the possible acceptance of loads at points C and E while advising against the same in point B, D and F. The furniture performed optimally without failure during the practical evaluation. The possible production of structurally sound and economical furniture through the understanding of loads acting on themas asserted by Carla and Edgar (2008) is further proven.

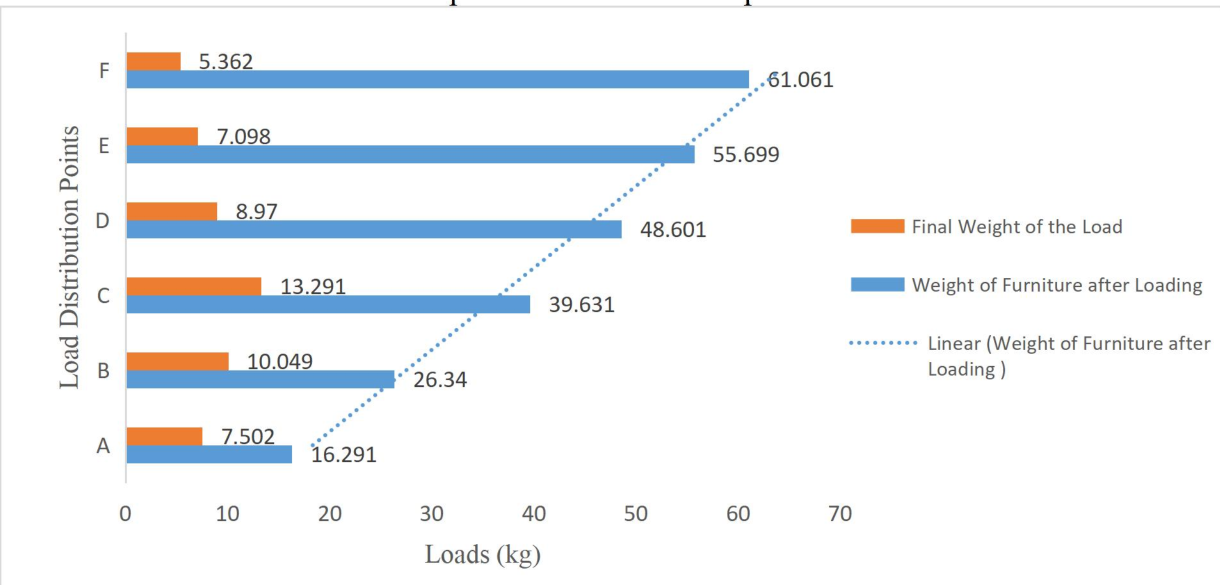

Figure 4. Progression and distribution of load on Glued laminated bookshelf

(a)Bookshelf without load ***(b) Load Point A*** ***(c) Load Point B***

(d) Load Point C *(e) Load Point D* *(f) Load Point F*

Plate 1a-f. Performance testing of bookshelf

4.0 Conclusion

This study was able to designed, analysed and performed practical evaluation on a glued-laminated bookshelf. The theoretical and experimental evaluation results for the structure record was adequate. The practical evaluation reveals that the shelf was able to carry and transmit a maximum load of 52.272kg (512N), with 7.502kg (73N), 10.049kg (98N), 13.291kg (130N), 8.97kg (87), 7.098kg (69N) and 5.362kg (52N) at loading points A, B, C, D, E and F respectively.

This study supplies background information in the design and load bearing capacity of a glued-laminated wooden shelf. The study further asserts the use of reasonable and representative loads for adequate designs assessment. It is recommended that the use of Computer Aided Design (CAD) software such as SOLIDWORKS, ANSYS be explored in the design and analysis of furniture. Likewise, the theoretical aspect of furniture design be emphasized to better the practical results for the producer and client.

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