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MECHANICAL QUALIFICATION OF GREEN GLUED LAMINATED TIMBERS FROM THE CONGO BASIN TOWARDS PRESERVATION OF FOREST SPECIES DIVERSITY

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This study investigates the bending performances of full-size and green glued laminated timber (glulam) beams, manufactured under a tropical climate. Two types of beams were prepared: mono-species and mixed-species glulam. The mono-species glulam with uniform layup were manufactured using abura (*Mitragyna ciliata*) and dabema (*Piptadeniastrum africanum*). The mixed-species glulam with balanced layup were manufactured by associating difou (*Morus mesozygia*) and abura, and tali (*Erythrophleum ivorense*) and dabema. These species were selected in the framework of a sustainable development of the glulam industry in Congo Basin, and clustering of their technological properties. A one component polyurethane adhesive was used, and the beams were dried artificially using vacuum. Pure bending tests were performed and the results showed an optimal bondlines thickness that ranged from 0.1 to 0.3 mm. Failure occurred in the solid woods indicating a satisfatory bonding quality of the glulam products. The strength properties of the glulam and solid woods presented compatible trends. Findings of this study showed that it is possible to develop high mechanical performance glulam products while improving the valorisation of lesser-known species, thus preserving the forest diversity in the Congo Basin.

Keywords: Tropical glulam, lesser-known timber species, vacuum drying, valorisation, bending strength

INTRODUCTION

Glued laminated timber (glulam) is a high-performance composite material in the construction sector. For a given section size, glulam components are more durable and stronger than sawn timber. They can span large distances without intermediate columns and may be composed of one, two or three timber species (Ayina & Etaba 1996, Gerard 1999, Lissouck et al. 2016a). As a consequence, they offer the possibility of utilising lesser-known timber species, which may result in the diversification of harvested forest species. This reduce the exploitation of highly valued trees, thereby preventing deforestation (Lissouck et al. 2018). By gluing together solid wood members, a homogenisation of their mechanical behaviour is reached and a reduction of their natural variability is achieved, while optimising their mechanical behaviour in structure (Fink 2014, Kandler & Fussl 2017, Donadon et al. 2020, Xue et al. 2021). In addition, glulam products can be manufactured in developing countries without significant levels of industrial resources (Ayina & Etaba 1996). They can be primarily manufactured without higher-grade finishing, and then used as 'feedstock product' for secondary wood processing industries (Gérard 1999). Despite the various potentials of these products, there is a lack of information concerning their mechanical strength, especially when they are manufactured with non emblematic timber species at a full-size scale. Indeed, in tropical countries, research has focused on the mechanical characterisation of solid wood, but studies on glue laminated timber are almost non-existent (Ndong Bidzo et al. 2021).

The feasibility of manufacturing glulam using timber species from the Congo Basin has been previously investigated (Ayina & Etaba 1996, Bedel & Gautier 1972, Gérard 1999, Guiscafré & Sales 1975, Guiscafré & Sales 1977, Guiscafré & Sales 1980, Sales 1979, Sales 1981, Sales 2003). The forest species considered in these studies include acajou (*Khaya spp.*), frake (*Terminalia superba*), bilinga (*Nauclea diderrichii*), bomanga (*Brachystegia mildbraedii*), movingui (*Distemonanthus benthamianus*), sapelli (*Entandrophragma cylindricum*), sipo (*Entandrophragma utile*), tiama (*Entandrophragma angolense*) and makoré (*Tieghemella* sp.). Species such as acajou, sapelli and tiama are considered endangered (IUCN 2013). The results underlying their valorisation aptitude in glulam need to be updated, as they are not confirmed in glulam manufacturing with lesser-known and non endangered species. Moreover, the development of glulam using local timber species, as one of the key products of the wood processing industries, could ensure an increase and a diversification of local forest economy, since Central African countries recently banned the export of timber or logs. Indeed, a glulam factory may generate good income, since it consumes big volumes of timber, at least 5000 m^3 per year for its profitability (Bourreau 2011). Glulam has potential for increasing the timber value of poorly shaped logs (from which it is difficult to obtain satisfying size elements), downgraded timber with defects that need to be removed (not allowed for exportation) and sawmill wastes generally used as fuelwood (Gerard 1999). Ndong Bidzo et al. (2021) carried out experimental studies on the mechanical behavior of mixed glulam manufactured with three tropical species, namely niove (*Staustia kamerunensis*), padouk (*Pterocarpus osun*) and ozigo (*Dacryodes buettneri*). Nevertheless, investigations were not conducted at the scale of the product, in addition, ozigo is endangered (Hills 2020).

In order to develop a sustainable glulam industry in the Congo Basin, Lissouck et al. (2018) elaborated a multicriteria decision support model to select forest species that meet both preservation requirements (non endangered species according to IUCN redlist, availability and regeneration potential), technological aptitudes (i.e. good aptitude for bonding, durability and processing difficulty) and their uses for non-timber purposes. Species that meet these criteria include abura (*Mitragina ciliata*), dabema (*Piptadeniastrum africanum*), tali (*Erytrophleum ivorense*) and difou (*Morus mesozygia*) (Table 1). These species have potential to be used in structural applications such as poles, piles and bridges (CIRAD 2011). They actually present a marginal economical interest compared to the most exploited species in the subregion. Indeed, five species represent 70% of the industrial exploited timber species in central Africa, i.e., ayous (*Triplochiton scleroxylon*), sapelli, azobé (*Lophira alata*), iroko (*Milicia excelsa*) and tali. The most frequently exploited species include ayous, movingui, iroko, sapelli and bilinga (Eba'a-Atyi et al. 2013).

The artificial drying of the timber species is among the key industrial process prior to gluing operations. This may lead to certain incidents and defects (superficial or internal cracks, severe deformations, cups and bows). These defects may be amplified while using some hardwoods from the Congo Basin forests, characterised by a high shrinkage rate. When the drying process is successfully achieved, the gluing aptitude may decrease due to some specificities of tropical hardwoods like resin exudation and low porosity (Bourreau et al. 2013, FCBA 2008, Gerard 1999). To provide solutions, researchers have previously investigated green gluing of less

Table 1 Multicriteria classification of the timber species from the Congo Basin (Lissouck et al. 2018)

	Multicriteria consensus level		
	High (the timber species maximises the set of criteria)	Moderate (the consensus potential is not maximized in the whole set of criteria, but it is not the lowest)	Insufficient (the consensus potential is the lowest)
Timber species	Bete, Dabema, Longhi, Lotofa, Niové, Tali	Akossika, Alep, Andoung, Angueuk, Aningré, Awoura, Bahia (abura), Bomanga, Bubinga, Ekaba, Difou, Ebiara, Ekoune, Frake, Gombe, Kanda, Kekele, Landa, Limbali, Movingui, Nieuk, Oboto, Padouk, Pao rosa, Tchitola	Acajou, Afrormosia, Aielé, Avodire, Ayous, Azobé, Bilinga, Bodioa, Bossé, Dibetou, Doussié, Ebene, Emien, Essia, Eveuss, Eyong, Faro, Framire, Iatandza, Igaganga, Iroko, Izombe, Kondroti, Kosipo, Kotibe, Koto, Lati, Makore, Moabi, Mukulungu, Naga, Okan, Olon, Onzabili, Ovoga, Ozigo, Sapelli, Sipo, Tiama, Tola, Wenge, Zingana

dense timber species such as ayous and frake (Njungab et al. 2013a, Njungab et al. 2013b, Lissouck et al. 2016b). Results showed that these species were suitable for manufacturing green glued laminated timber (GGLT). Nevertheless, investigations were not conducted at the scale of the product. At the industrial level, the green gluing technique may allow some energy saving and reduce the degradation of material integrity (Makomra et al. 2020). On the other hand, green wood machining is easier to process than dried wood. This advantage could be interesting for the valorisation of several heavy timber species while developing tropical GGLT.

The main objective of this work is to qualify the mechanical strength of GGLT from the Congo Basin at the scale of the product, manufactured in high moisture content (MC) conditions in tropical climate.

MATERIALS AND METHODS

Materials

In this work, four tropical timber species were selected, i.e., abura, dabema, difou and tali. These species are suitable for sustaining the market position of glulam products (Table 1). They have the potential to provide good consensus among glulam stakeholders for sustainable use in the glulam industry, and they are non endangered. They can be glued correctly and used for the manufacture of GLT beams. They can be easily processed and their value for use as non-timber forest products is the lowest (Lissouck et al. 2018). Each species belongs to a cluster (Table 2) in which the behaviour and the quality of the glulam product may be specific (Lissouck et al. 2016 a). Some physical and mechanical characteristics

Table 2 Clustering of the timber species from the Congo Basin (Lissouck et al. 2016)

Clusters	Timber species		Properties	Specific gravity	Average tangential shrinkage	Average radial shrinkage	MOR (MPa)	MOE (MPa)
Cluster 1	Kondroti, Tola	Ako, Ayous, Emien, Fromager, Ovoga	Mean	0.43	0.194	0.096	55	8354
			Standard deviation	0.07	0.022	0.019	13	1815
			COV (%)	17	11	20	23	22
Cluster 2	Acajou, Bosse, Dibetou, Framire, Iatandza, Kosipo, Sipo, Tiama	Abura, Aielé, Aningre, Bomanga, Ekoune, Frake, Faro, Ilomba, Iroko, Naga, Nieuk, Olon, Onzabili, Ozigo	Mean	0.57	0.227	0.139	79	11967
			Standard deviation	0.05	0.025	0.013	10	1208
			COV (%)	9	11	9	12	10
Cluster 3	Afrormosia, Bilinga, Igaganga, Izombe, Eyong, Koto, Makore, Sapelli	Akossika, Andoung, Bete, Dabema, Ebiara, Ekaba Gombe, Kanda, Kekele, Landa, Tchitola	Mean	0.67	0.290	0.156	96	14094
			Standard deviation	0.05	0.032	0.012	6	1157
			COV (%)	7	11	13	6	8
Cluster 4	Doussié, Kotibe	Difou, Essia, Longhi, Movingui, Niove, Oboto, Padouk	Mean	0.79	0.252	0.160	123	16047
			Standard deviation	0.05	0.012	0.017	15	2210
			COV (%)	6	5	10	12	14
Cluster 5	Bodioa, Mukulungu, Zingana	Awoura, Bubinga, Lati, Limbali, Lotofa, Okan, Pao rosa, Tali	Mean	0.87	0.339	0.218	130	19024
			Standard deviation	0.08	0.022	0.042	10	1819
			COV (%)	9	7	19	8	10
Cluster 6	Azobe, Moabi, Wenge	Alep, Eveuss	Mean	0.98	0.386	0.273	155	22504
			Standard deviation	0.10	0.017	0.025	11	1995
			COV (%)	10	4	9	7	9

MOR = modulus of rupture, MOE = modulus of elasticity, COV = coefficient of variance of the selected species are presented in Table 3. Artisanal sawnwood used in this study was procured from the local wood market in Yaounde Cameroon; sawn boards of 5000 mm length, 150 mm width and 26 mm thickness were used. A one-component polyurethane with a viscosity of 1000 mPa s^{-1} at 20 °C, patented for green plywood gluing, was used as adhesive.

Fabrication of green-glued laminated timbers

Sawn boards were cut, planed and organised into two families of twin lamellae, the first family intended for green gluing and the second for the determination of their vibratory modulus of elasticity. The lamellae were planed in order to obtain straight elements of uniform dimensions and to easily identify potential defects on the surface of the wood. After planing, the thickness of the lamellae was about 22 mm, a width of 130 mm and a length of 2400 mm (Figure 1). Defects free lamellae were sorted and used.

The vibratory modulus of elasticity (MOEvib) was computed by using equation 1 (Mvogo et al. 2011). This parameter makes it possible to organise optimally the lamellae in a glulam (Faye 1997). More precisely, lamellae with higher MOE_{vib} were placed in the outer part of the glulam and lamellae with lower MOEvib were placed in the inner part of the product.

$$MOE_{vib} = 4\rho L^2 f_1^2 \tag{1}$$

where f_1 is the frequency of the first mode of vibration, L and ρ are the length and volumic mass of the lamella respectively. Three vibratory tests were performed on each lamella.

In order to limit the pollution of gluing surfaces by the potential migration of wood extractables such as resin, the lamellae were planed for a second time and cleaned with an

Table 3 Physical and mechanical characteristics of the selected timber species (CIRAD 2011)

Characteristics	Timber species			
	Abura	Dabema	Difou	Tali
Density at 12% moisture content (kg m^{-3})	600	700	840	910
Saturation fibre point (SFP) (%)	32	27	21	26
Volumetric shrinkage coeffient (%)	0.44	0.55	0.46	0.57
Average tangential shrinkage (%)	8.9	8.5	5.7	8.4
Average radial shrinkage (%)	4.3	3.8	3.2	5.1
Average anisotropic ratio $R_t R_r^{-1}$	2.1	2.2	1.8	1.6
Ultimate compressive strength (MPa)	46	58	86	79
Ultimate bending stress (MPa)	78	97	143	127
Elasticity modulus (GPa)	11	15.5	18.5	19.5

(1a) (1b)

Figure 1 Illustration of the lamellas after planing, (1a) a view of lamellae, (1b) surface aspect of abura wood after planing air blower just before starting gluing operations. During gluing, the average moisture content of the lamellae varied from 46 to 63% during gluing. Four types of glulam were manufactured: (1) a mono-species glulam manufactured with abura wood, (2) a mono-species glulam manufactured with dabema wood, (3) a mixed-species manufactured using difou and abura lamellae and (4) a mixed-species manufactured by associating tali and dabema lamellae. The mixed beams were found suitable since difou and tali are dense species. In the mixed beams, tali and difou woods were arranged in the outer layers, while abura and dabema woods were placed in the inner layers. A total of 6 lamellae were used in each beam. The lamellae were arranged in each beam so as to obtain a symmetrical distribution of vibratory MOEs. The adhesive was spread with a rate of 200g m^{-1} per side (400 g m^{-2} for each glue joint) (Figure 2). Five beams were manufactured for each type and designed for mechanical tests. Two additionnal beams were manufactured for calibrating the parameters of the bending test.

The opening and closed assembly times were 5–7 minutes and 35–40 minutes for each beam respectively. Each beam was keept under a clamping pressure of 1.2 MPa for a duration of 18 hours. The beams were stabilised for 15 days after the gluing operations. The duration was much longer than polymerisation of the adhesive (4 days). The side faces of the beams were planed in order to obtain straight and regular cross sections.

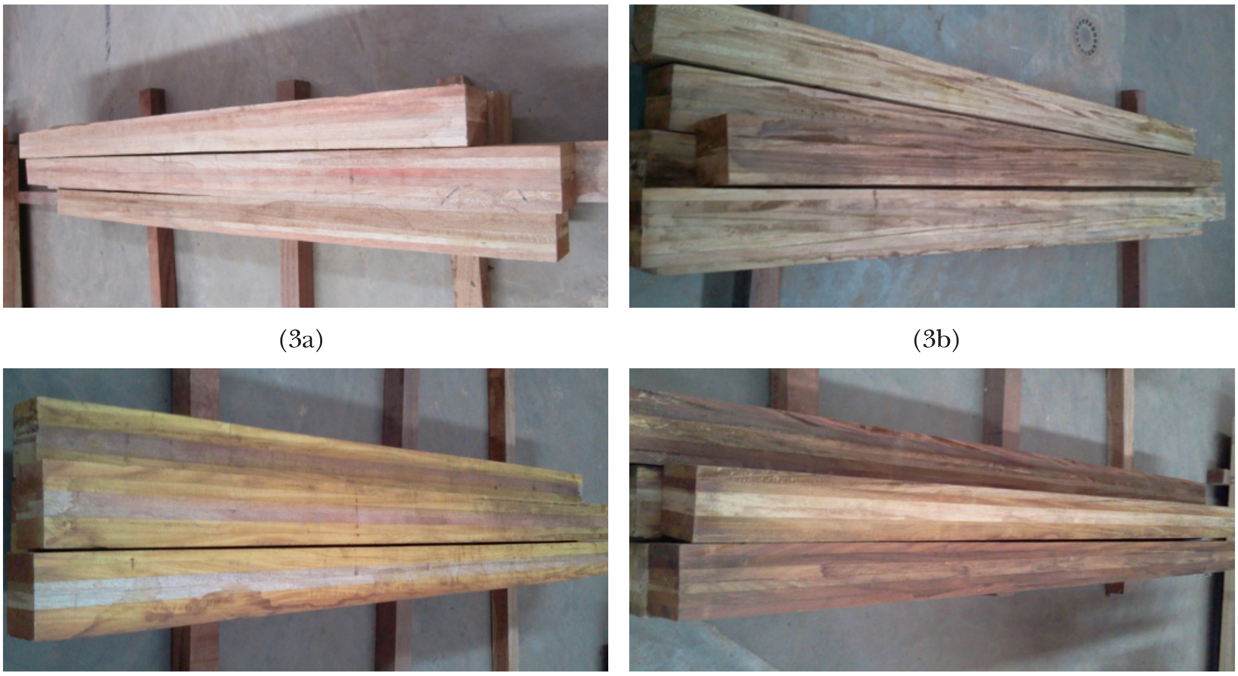
Glulam drying and bondlines thickness measurement

The beams were first subjected to a natural drying process which lasted for three months. At the end of that phase, the MC level was reduced to around 30%. The principle of vacuum drying was retained due to its interesting speed and the good final quality of the products (Assouad 2004). A discontinuous vacuum dryer of 4.5 kW was used. The homogeneous beams were dried separately from the mixed beams. The first phase of the drying process consisted of heating with hot air at temperature 50 °C for 90 minutes. This is the convective phase of drying which takes place at normal atmospheric pressure. Then the cell was subjected to a vacuum pressure which lasted for 60 minutes. In such a condition, the migration of water from the core to surface is accelerated. The second phase consisted of subjecting the cell to vacumm pressure for 60 minutes. This also accelerates the migration of water from the core to the suface. In the final phase the cell was humified with water vapor in order to limit the apparition of cracking effects on the surface of the beams. These three phases were repeated until the moisture content of the wood reached 20%. Thereafter, the vacuum drying continued with vacuum and heating phases only. After four days, the moisture content of the beam was 17%, corresponding to the average equilibrium moisture content of wood in a tropical climate (15%). Figure 3 illustrates the aspect and straigthness of the beams after drying. Joint thickness measurements were carried out on all bonds using an optical microscope with a magnification factor of 7 and an accuracy of 0.05 mm.

Four-point bending test

The 4-point bending test was carried out in accordance to EN408 standard (Figure 4). This

Figure 2 Glue burrs on a side face of a mixed difou-abura glulam beam



(3a) (3b)

(3c) (3d)

Figure 3 Aspects and straightness of the glulam beams at the end of the drying process, (3a) abura glulam, (3b) dabema glulam, (3c) mixed difou-abura glulam, (3d) mixed tali-dabema glulam

was aimed at quantifing the modulus of elasticity (MOE) and modulus of rupture (MOR) while describing the failure process of the glulam, where failure happens inside the wood tissue. In this case, the adhesive has fulfilled its function (Frihart 2004). The vertical displacement at the mid-span of the beam is calculated by the equation below (Picard 1992):

$$V = \frac{Pa(3L^2-4a^2)}{24EI} \qquad (2)$$

where I is the moment of homogeneised inertia of the cross-section, E is the elastic modulus of the glulam beam, L is the span of the beam (1550 mm), d is the distance between the two supports (550 mm), a is the distance between one support and the nearest loading head, b and h are respectively the width (about 120 mm) and the depth (about 120 mm) of the beam (Figure 4).

From equation 2, the static elasticity modulus MOE (MPa) was estimated as follows:

$$MOE = \frac{\Delta P}{\Delta V}\,\frac{(3L^2-4a^2)a}{24I} \qquad (3)$$

where $\frac{\Delta P}{\Delta V}$ is the slope of the linear part of the load/displacement curve.

The ultimate bending strength MOR was expressed as follows:

$$MOR = \frac{6aP_{max}}{bh^2} \qquad (4)$$

where Pmax is the ultimate load of the beam in bending.

To compare the mean values of the MOR and MOE of glulam, a one-way analysis of variance (ANOVA) was performed using the Minitab 16 statistics software. To find means that are significantly different from each other, the Tukey's range test was used.

RESULTS AND DISCUSSION

Vibratory elastic moduli of lamellae

The vibratory MOE values of the lamellae are presented in Table 4. The sample showed average MOE values of 8386 MPa for abura, 10391 MPa for dabema, 11399 MPa for difou and 13397 MPa for tali. For each species, the minimum and maximum values were provided, as well as the corresponding standard deviations. Nyobe (2014) determined parameters while investigating the mechanial strength of okan by

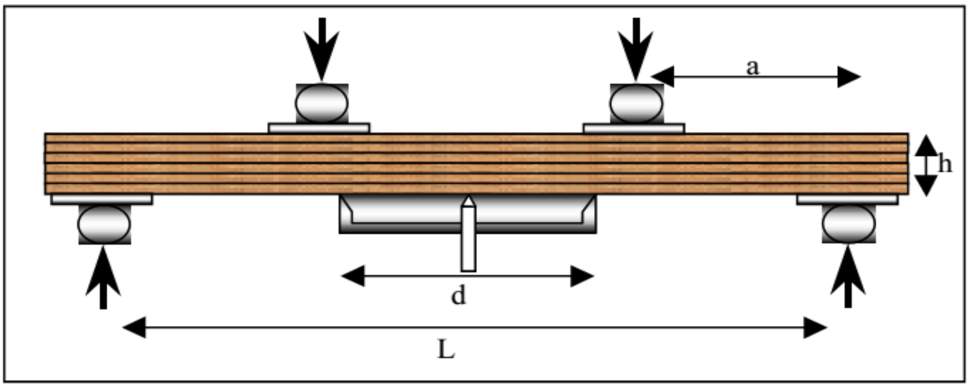


Figure 4 The 4 point-bending test (EN 408)

Table 4 Vibratory modulus of elasticity (MOE) of the lamellae at the green state

Timber species	Abura	Dabema	Difou	Tali
Mean values of vibratory MOE (MPa)	8 386	10 391	11 399	13 397
Standard deviation (MPa)	817	1 013	859	1 950
Minimal value (MPa)	6 283	6 793	9 655	10 419
Maximal value (MPa)	9 406	12 655	13 745	17 499

using specimens with similar dimensions. Okan wood presents similar strength properties with tali at the material scale (Lissouck et al. 2016a). It was found that the vibratory MOE may vary from 12 000 to 18 000 MPa, with a mean value of 14 000 MPa. The MOE vibratory values in this study may serve as reference values for further studies.

Bondline thickness

The GGLT showed joint thicknesses 0.22 ± 0.10 mm for abura-abura bonds and 0.21 ± 0.07 mm for dabema-dabema bonds. Lower values were obtained in mixed glulam. The difou-difou and tali-tali joints in the mixed GGLT had respective thicknesses of 0.19 ± 0.10 mm and 0.14 ± 0.09 mm. The thickness of the tali-dabema joints was 0.14 ± 0.05 mm. A same trend was observed in difou-abura glue joint (0.13 ± 0.05 mm). The thickness of an adhesive joint is one of the main factors influencing the mechanical behavior of bondlines. The resistance of the bondline increases rapidly from very small thicknesses (less than a few tenths of a millimeter), passes through an optimum, and then decreases (Bretton & Villoutreix 2005). For polyurethane adhesives, this optimum thickness may vary between 0.1 to 0.3 mm (Jeandreau 2007). The observations showed that gluing parameters allowed to obtain optimum bondlines thickness in various types of glulam.

Experimental responses of the green-glued laminated beams under pure bending

Under pure bending, the green-glued laminated beams showed two distict behaviours (Figure 5): (i) linear behavior which increases until the apparition of a sudden crack (beams 1 and 4 in Figure 5a, specimens 1 and 2 in Figure 5c) and (ii) ductile behavior for the dabema glulam (Figure 5b). The ductile behavior of dabema GLT could be the result of the dabema wood in tension zones of the beam. In each beam, the collapse was initiated in the tensile zone. In the case of the abura glulam, a complete dislocation of the beams was observed at the end of the test. In the other cases, the beams were partially dislocated and the specimens remained on the bending supports. The final deflections of abura beams ranged from 26 to 46 mm, while their ultimate load varied from 53 to 64 kN (Figure 5a). Dabema glulam showed a more tenacious behavior in which the final deflections ranged from 37 to 57 mm, and an ultimate strength varying from 81 to 101 kN (Figure 5b). Nevertheless, the specimen "dabema 6" collapsed with a low ultimate strength. Indeed, the average MC of the lamellae of the specimen was about 80%, which is higher than the maximum MC of 70% required during gluing, resulting a

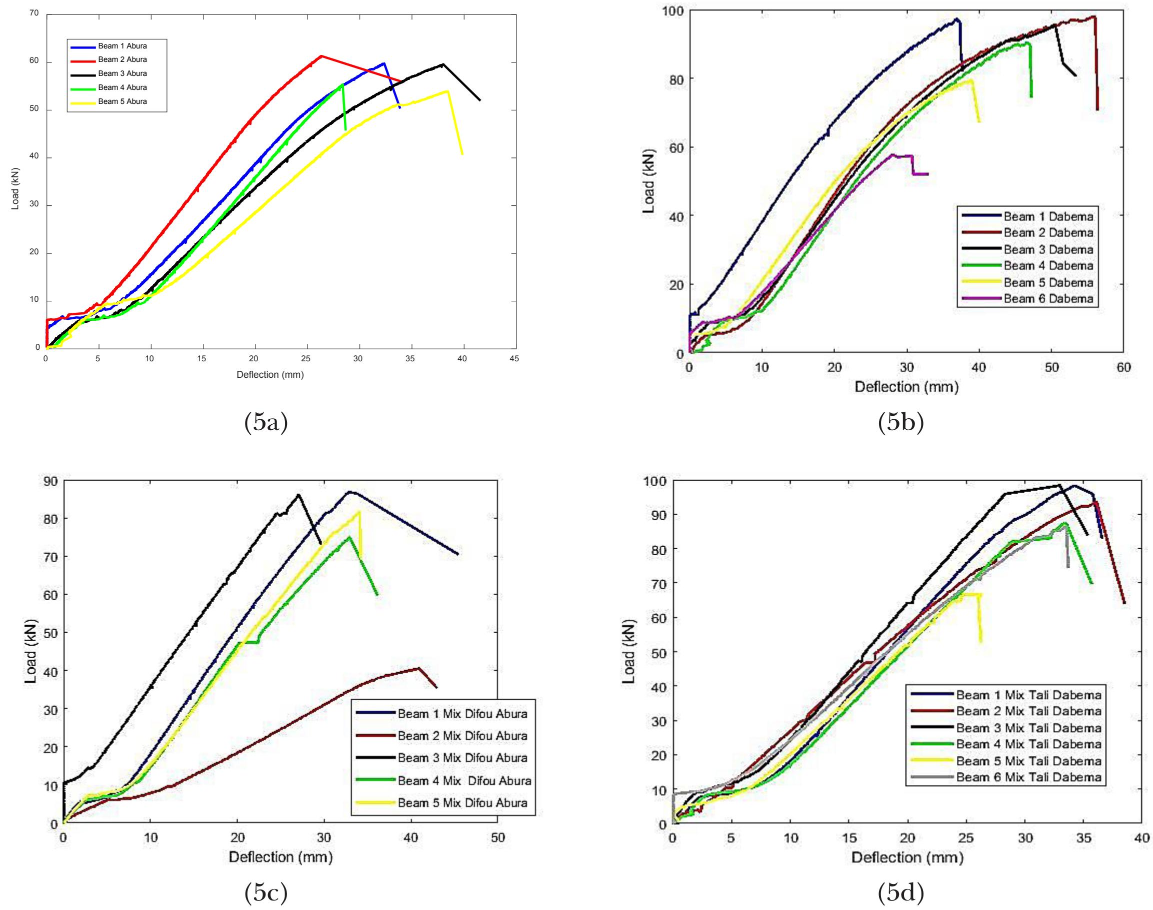


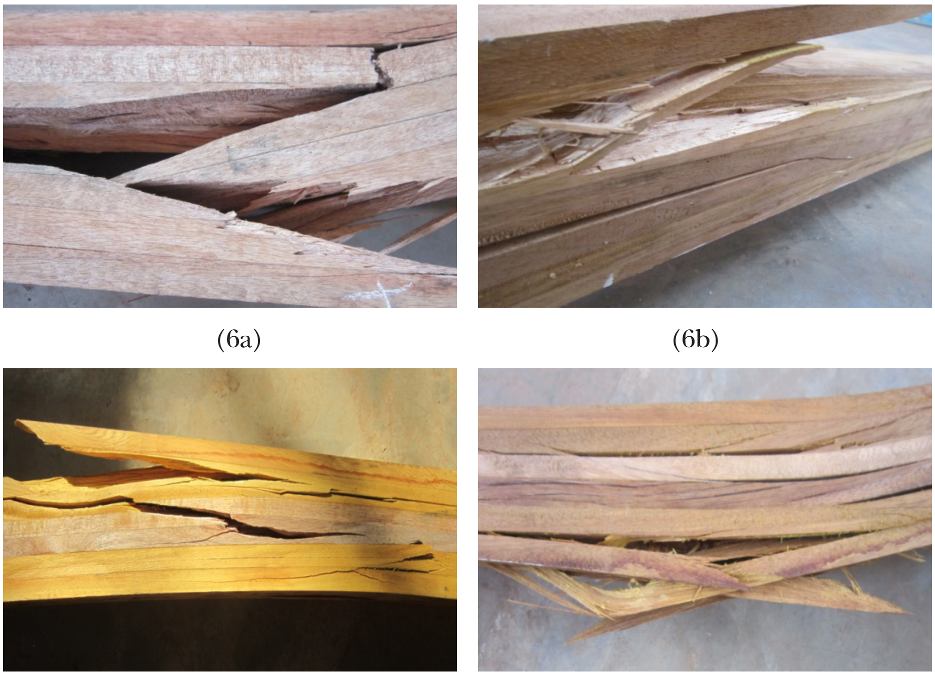
Figure 5 Load-deflection curves of the glulam beam in pure bending, (5a) homogeneous abura glulam, (5b) homogeneous dabema glulam, (5c) mixed difou-abura glulam, (5d) mixed tali-dabema glulam

low quality of adhesion. As a consequence, the rupture was initiated in the glue joint instead of the wood. A collapse characterised by sudden cracks was observed in the mixed difou-abura beams (Figure 5c). Their ultimate loads varied from 77 to 90 kN, corresponding to deflections varying from 27 to 37 mm. The ultimate load of tali-dabema beams varied from 85 to 100 kN and the ultimate deflections from 33 to 38 mm.

The experimental responses of the beams are in accordance with experimental investigations available in the literature. For instance, Ndong Bidzo et al. (2021) reported a ratio ultimate load-volume of beams that vary from 0.0020 N mm^{-3} to 0.0044 N mm^{-3}, while mixed glulam without abutmens were tested. This is similar to observations in this study with ratios that range from 0.0018 N mm^{-3} to 0.0032 N mm^{-3}. The load-deflection curves also showed similar trends to those presented in Ndong Bidzo et al. (2021) (Figure 5) . Typical failure mode observed during the pure bending test is presented in Figure 6. For all beams (except glulam specimen dabema 6 mentionned previously in Figure 6b), failure begins at the bottom lamella in the tensile zone. The rupture process resulted from a detachment of the wood fibres which overlapped in the tensile zone of the external lamellae. A ductile failure was observed specifically in dabema glulams. These modes are similar to those described by Mohamad et al. (2012), Ndong Bidzo et al. (2021) and Mohamad et al. (2019). The GGLT showed a satisfying behaviour in bending. This validated their mechanical bending strength and quality.

Mechanical and physical characteristics of green-glued laminated beams

The strength properties of GGLT and corresponding variation coefficients are presented in Table 5. The highest average MOR (78.2 MPa) was obtained in mixed tali-dabema beams, followed respectively by homogeneous



(6a) (6b)

(6c) (6d)

Figure 6 Illustration of the rupture facies of each glulam beam; (6a) homogeneous abura glulam, (6b) homogeneous dabema glulam, (6c) mixed difou-abura glulam, (6d) mixed tali-dabema glulam

dabema products (73.1 MPa), mixed difou-abura beams (70.1 MPa) and abura beams (54.1 MPa). These values were in agreement with the average density of the beams. The correlations between the resistance properties of GGLT are presented in Figure 7. The one-way anova test on MOR revealed a p-value of $1.68.10^{-5}$, less than the treshold value of 0.005. As a consequence, the hypothesis of the equality in mean values was rejected. Moreover, a significant difference was observed between abura and the other glulam types. The average MOR value of dabema,

Table 5 Strength properties of green glued laminated timaber (GGLT)

		Abura	Dabema	Difou-abura	Tali-dabema
	Mean	647	814	767	999
Volumic mass (kg m^{-3})	Ecart-type	89	57	33	24
	Cov (%)	14	7	4	2
	Mean	54.1	73.1	70.1	78.2
MOR (MPa)	Standard deviation	4.5	13	5.5	6.7
	Cov (%)	8	18	8	9
	Mean	8 640	12 330	11 860	13 291
MOE (MPa)	Standard deviation	684	1265	1227	997
	Cov (%)	7.9	10.3	10.5	7.5
	Mean	0.085	0.079	0.091	0.078
MOR per volumic mass (MPa.m^3 kg^{-1})	Standard deviation	0.015	0.012	0.008	0.007
	Cov (%)	18	13	8	9
	Mean	60.4	87.5	86.2	95.5
Ultimate load (kN)	Standard deviation	4.2	15.9	5	5.9
	Cov (%)	7	18	6	6

COV = coefficient of variance

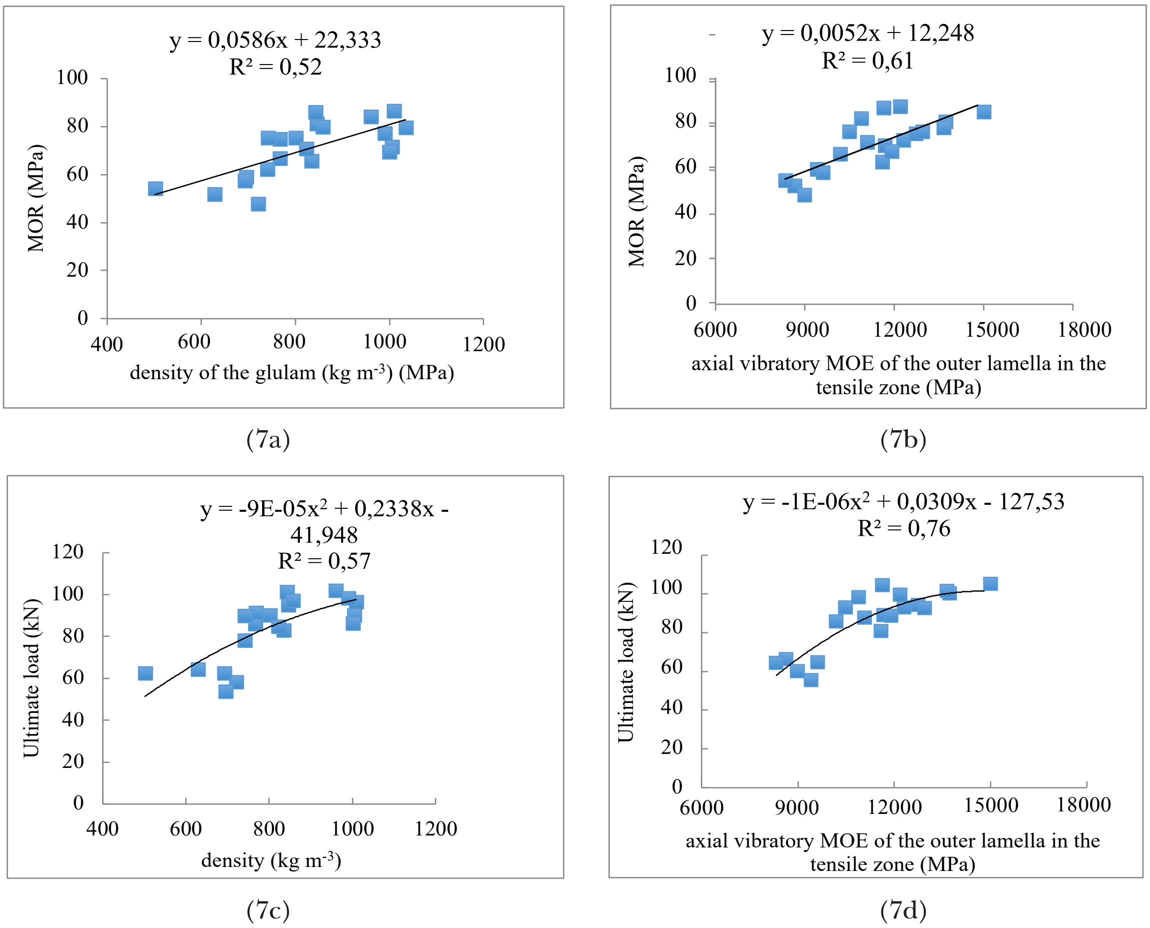


Figure 7 Correlations in strength properties, (7a) correlation between modulus of rupture (MOR) with volumic mass, (7b) correlation between MOR with axial outer vibratory modulus in the tensile zone, (7c) correlation between the ultimate load and the volumic mass, (7d) correlations between the ultimate load with with axial outer vibratory modulus in the tensile zone

difou-abura and tali-dabema glulam specimens was not significantly different from each other. A very similar trend was observed concerning the MOE. The difference in MOR between abura and difou-abura glulam established the interest of mixing timber species while obtaining strength-to-weight ratio. Such a ratio was the highest in difou-abura glulam (0.091 MPa.m^3 kg^{-1}) compared to tali-dabema glulam (0.078 MPa.m^3 kg^{-1}) (Table 5). The difference in average MORs between mixed tali-dabema and dabema glulam is not significant due to the toughness of dabema wood and the brittleness behaviour of tali wood. The outer lamella in the tensile zone appeared to be a good predictor of the mechanical strength compared with density of glulam (Figure 7a and 7b). The corresponding R^2 coefficients (linear correlations) were 0.52 and 0.61 respectively. Polynomial correlations were found between the ultimate load and the two parameters mentionned previously (Figure 7c and 7d). The highest R^2 value was obtained in correlation between the ultimate load and axial vibratory MOE of the outer lamella in tensile zone (R^2 = 0.76). The average MOE value increased with the density of glulam. It varied from 8,640 MPa for abura glulam, 12,330 MPa for dabema glulam, 11,860 MPa for mixed difou-abura products and to 13,291 MPa for mixed tali-dabema specimens (Table 5). It was found that these values were globally compatible with the vibratory moduli of the lamellae presented in Table 4.

The MOR values of the glulam were close to those of solid woods. It should be noted that the glulam products were manufactured without abutments. For instance, the MOR of the mixed tali-dabema glulam is 78.2 MPa, slightly lower than the average value of 84 MPa, (Lissouck 2014). Ayina and Etaba (1996) found an average MOR of 61.3 MPa while testing glulam products manufactured with abutments by using bilinga wood (density about 800 kg m^{-3} at 15% MC).

The MOR of the bilinga plancks was 80 Mpa. The results are in accordance with Benoît et al. (2009) and Faye (1997), who established that MOR value of a glulam product is generally lower than the MOR of external lamella in tensile zone, when the gluing quality of the product is correct.

CONCLUSION

The main objective of this study was to qualify the mechanical strength of GGLT from Congo Basin at the scale of the product, manufactured in high MC conditions under tropical climate. Four timber species presenting a high valorisation potential for the glulam industry were selected, namely abura, dabema, difou and tali. Their economical value is marginal compared to the most exploited timber species in central African forests. Homogeneous and mixed beams were manufactured at a green state, dried and tested in pure bending. Their mechanical strength properties were quantified. Results showed that the quality of adhesion was satisfying in the products since the failures started in the external solid wood located the tensile zone. As a consequence, the strength properties of the glulam and the corresponding solid woods exhibited compatible trends. The findings of the study showed that it is possible to develop high-performance GGLT while preserving the diversity of timber species in Congo Basin.

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