Characterisation and statistical modelling of shear strength in 12 hardwood timber species from the Congo Basin

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Photo 1.
Example of outdoor application of three of the characterised species, Azobé, Okan and Tali: https://www.houtindegww.nl/project/het-wrakhout-wenduine/
"Het Wrakhout" bridge combined with a cycle path and pedestrian walkway - Welduine, Belgium.
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Doi : 10.19182/bft2024.360.a37284 – Droit d'auteur © 2024, Bois et Forêts des Tropiques – © Cirad – Date de soumission : 9 août 2023 ; date d'acceptation : 18 avril 2024 ; date de publication : 1er juin 2024.

Citer l'article / To cite the article
Ndiapi O., Njankouo J. M., Ohandja L. M. A., Gérard J., 2024. Characterisation and statistical modelling of shear strength in 12 hardwood timber species from the Congo Basin. Bois et Forêts des Tropiques, 360 : 27-40. Doi : https://doi.org/10.19182/bft2024.360.a37284

Bois et Forêts des Tropiques – ISSN: L-0006-579X
Volume 360 – 2nd quarter – June 2024 – p. 27-40

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RÉSUMÉ

Caractérisation de la résistance au cisaillement du bois de 12 essences feuillues du Bassin du Congo et modélisation statistique

La résistance au cisaillement est une propriété du bois fondamentale pour la conception de produits et de constructions à base de bois. Les connaissances actuelles sont insuffisantes pour prédire cette propriété, principalement en raison du grand nombre d'essences présentes dans le Bassin du Congo. L'objectif principal de cette étude était de proposer une qualification préliminaire du cisaillement pour les essences du Bassin du Congo, en prenant en compte sa variabilité. Pour ce faire, nous avons étudié 12 essences aux propriétés très différentes, de la moins dense à la plus dense. La résistance des bois au cisaillement a été déterminée expérimentalement selon les spécifications des normes européennes, à l'échelle du matériau bois utilisé. Une analyse statistique a été réalisée. Pour réduire la variabilité de la résistance au cisaillement, les essences ont été réparties en quatre groupes distincts selon les spécifications de l'Institut FCBA. En vue de proposer des contraintes admissibles qui faciliteraient la prise de décision, la qualité relative de l'ajustement de cinq modèles probabilistes de distribution de la résistance au cisaillement a été évaluée (normale, log-normale, exponentielle, Weibull à 2 paramètres et Weibull à 3 paramètres). Les résultats de la régression géométrique (R^2 = 0,81) montrent que la résistance au cisaillement est fortement corrélée à la densité. Elle peut être prévue de manière plus fiable avec la distribution de Weibull à trois paramètres qu'avec les autres distributions. Les résultats de cette étude ouvrent de nouvelles perspectives au regard de la résistance au cisaillement, qui sont à prendre en compte pour la conception de produits bois à partir d'essences tropicales du Bassin du Congo.

Mots-clés : ANOVA, valeur caractéristique, essences feuillues tropicales, qualité des bois de feuillus, conception fiable, distribution statistique, Bassin du Congo.

ABSTRACT

Characterisation and statistical modelling of shear strength in 12 hardwood timber species from the Congo Basin

Shear strength is a wood property that is fundamental to the design of wood-based products and constructions. This property cannot currently be predicted due to insufficient knowledge, primarily because of the large number of timber species found in the Congo Basin. The main aim of this study was to provide a preliminary qualification of shearing in Congo Basin timber species, with consideration for its variability. For this purpose, we studied 12 timber species with very different properties, from the least dense to the densest. Their shear strength was determined experimentally using European standard specifications, on the scale of the wood material used. A statistical analysis was conducted. To reduce shear strength variability, the species were assigned to four distinct clusters defined according to FCBA Institute specifications. With a view to developing allowable design stresses to facilitate decision-making, we evaluated the relative goodness-of-fit of five probabilistic shear strength distributions (normal, lognormal, exponential, Weibull 2 parameters and Weibull 3 parameters) that are used in wood-related applications. The results of geometric regression (R^2 = 0.81) show that shear strength is well correlated with density. Shear strength can be more reliably predicted with the three-parameter Weibull distribution than with the other distributions. The findings of this study open up new prospects to be considered for the design of wood-based products with regard to shear, when using tropical timber species from the Congo Basin.

Keywords: ANOVA, characteristic value, tropical hardwood species, hardwood quality, reliable design, statistical distribution, Congo Basin.

RESUMEN

Caracterización y modelado estadístico de la resistencia a la cizalla en 12 especies de madera dura de la cuenca del Congo

La resistencia a la cizalla es una propiedad de la madera fundamental para el diseño de productos basados en la madera y en la construcción. Esta propiedad no se puede predecir actualmente a causa de la falta de conocimientos suficientes, principalmente por el gran número de especies madereras que se encuentran en la cuenca del Congo. El principal objeto de este estudio es proporcionar una cualificación preliminar de la resistencia a la cizalla en las especies madereras de la cuenca del Congo, considerando su variabilidad. Con este objetivo, estudiamos 12 especies madereras con propiedades muy diferentes, desde la menos densa a la más densa. Su resistencia a la cizalla se determinó experimentalmente mediante las especificaciones de las normas europeas, en la escala del material maderero utilizado. Se llevo a cabo un análisis estadístico. Para reducir la variabilidad de la resistencia a la cizalla, las especies se asignaron a cuatro grupos diferentes definidos según las especificaciones del Instituto FCBA. Con el objeto de desarrollar diseños con limitaciones permisibles que faciliten la toma de decisiones, evaluamos la relativa adecuación de cinco distribuciones probabilísticas de resistencia a la cizalla (normal, logonormal, exponencial, Weibull de 2 parámetros y Weibull de 3 parámetros) que se utilizan en aplicaciones madereras. Los resultados de la regresión geométrica (R^2 = 0.81) muestran que la resistencia a la cizalla tiene una buena correlación con la densidad. La resistencia a la cizalla puede predecirse de manera más fiable con la distribución de Weibull de tres parámetros que con las otras distribuciones. Los descubrimientos de este estudio abren nuevas posibilidades en el diseño de productos madereros respecto a la resistencia a la cizalla, utilizando especies de madera tropical de la cuenca del Congo.

Palabras clave: ANOVA, valor característico, especies de madera dura tropical, calidad de la madera dura, diseño fiable, distribución estadística, cuenca del Congo.

Introduction

The shear strength is a fundamental property of wood, generally used in timber structure design and modelling (Guitard 1987; Khokhar et al. 2010). It refers to the ability to resist internal slipping of one part upon another (Green et al. 1999). It can be considered such as the stress required to yield or fracture the material in the plane of material cross-section (Cubberly 1993). This makes it possible to identify the failure criteria of wood-based products subjected to combined stresses, such as tension-shear (Lavalette et al. 2012). Concerning engineered wood products such as glulam, the quality of the integrity between laminations can be assessed by using the wood shear strength (Aicher et al. 2018). The shear properties also drive the behaviour of timber structures under torque (Ayina and Morlier 1998). They are essential to calculate timber connections (Rodrigues et al. 2023). They can be needed while analysing the stability of columns and girders (Brandner and Schickhofer 2015). Despite the importance of these various arguments, there is a lack of knowledge concerning the shear strength of tropical hardwood species from the Congo Basin, which currently results in under- or over-dimensioning structural elements (Cunha et al. 2021). Indeed, these species are mainly appreciated for their interesting appearance and favourable physical and mechanical properties for structural use (Cunha et al. 2021; Lanvin et al. 2009). However, several databases describing the technological properties of central African species, such as Tropix 7.5.1 (Paradis et al. 2015) and ITTO (ITTO 2001), do not provide information concerning the shear properties. This can be explained by three main factors. The first one is the high diversity of central African timber species. More than 300 timber species present potential to be used for structural purposes, and about sixty of them are regularly exploited each year (Vivien and Faure 1995; Eba'a Atyi et al. 2013). Therefore, performing shear tests for all tropical timber species available in the Congo Basin would be time-consuming and expensive. The second factor is the lack of research initiatives aiming at the promotion of lesser-known species from the Congo Basin (Ayina 2002). Thirdly, standards concerning the use of hardwood products for structural purposes are missing in central African countries (Bourreau et al. 2013).

Due to the high number of exploited timber species in Central African forests, investigations concerning a fundamental property such as the shear strength need to be oriented towards the production of technical and simplified information for timber structure designers, industrial wood producers, and consumers. In that perspective, clustering specifications were elaborated by the FCBA Institute (2015). They enable the categorisation of hardwood species into groups, from lower to superior, based on their density range at 12% moisture content: "very light" (230-500 kg/m³), "light" (500-650 kg/m³), "medium heavy" (650-865 kg/m³), and "heavy" (865-1,000 kg/m³). These specifications are compatible with various classifications of hardwood timber species, formalised by authors such as Sallenave (1955) and Wong (2002). They are essential for meaningful and cost-optimal use of wood since the technological properties of most of the species are poorly known (Chowdhury et al. 2014). They also support the idea that, in each cluster, timber species may be interchangeably used for similar structural applications, since the wood density is one of the most critical parameters influencing the technological performance of timber products (Zziwa et al. 2006). They have the potential to be used as a tool for preserving highly exploited species and promoting the use of lesser-known species. They may be used easily for design purposes since the density is one of the most important parameters correlated with the technological features of timber species (natural durability, processing difficulty, mechanical strength, modulus of elasticity, gluing ability). The previous arguments support the idea that the FCBA Institute specifications are useful for: (i) designing hardwood timber structures since the density allows to define clearly the areas in which timber species may be used; (ii) analysing and simplifying the shear features of timber species from the Congo Basin. However, it is difficult to find reliable information on shear strength properties attached to these specifications. Using these specifications for investigating the distribution of the shear strength would draw a preliminary picture of that property, which is a main prerequisite needed while designing structures with timber species from the Congo Basin. This can be done by analysing the probabilistic models of the shear strength.

The use of probability functions to model the strength distribution of solid wood is of interest for two major reasons: the representation of the variability of the strength property and the reliability-based design procedures. Concerning the first point, it is well known that wood properties are highly variable within and between trees due to the complexity of wood formation (Pyorala et al. 2019). Such variability may be amplified in the presence of several timber species in a given specification cluster, even if their average densities are fairly similar. As a consequence, a timber strength property can be considered as a random variable. Not considering the variability while analysing a strength property may generate some unfavourable effects of any isolated element (in a construction project), in which constraints of security are extremely important and lead to structural inefficiency. Probabilistic models are therefore needed for specifying the variability (distribution) of the shear strength in each cluster. Moreover, it would be useful to analyse how the specification groups may influence the nature of the probabilistic model. The choice of probability distribution is generally guided by goodness-of-fit analysis. This analysis has been mainly made for strength properties in bending of timber (Modulus of Rupture, MOR) (Castera and Morlier 1994). However, scientific literature lacks information concerning the probabilistic modelling of the shear strength of timber species from the Congo Basin.

Concerning the second point, the probability distribution models of the shear strength are useful for (Foschi 2005): (i) calibrating the main parameters needed in a codified design (the 5% characteristic values, for instance); (ii) customising the design of a structure to meet specified performance with associated target reliability level. They enable more accurate safety analysis for hardwood timber structures (Czmoch 2021).

Several studies concerning the shear strength of tropical hardwood species were carried out and reported in the literature. Hernandez and Almeida (2003) investigated the effects of wood density and interlocked grain on the shear strength parallel to grain, based on three Peruvian timber species, namely Ishpingo (*Amburana cearensis* A.C. Smith), Pumaquiro (*Aspidosperma macrocarpon* Mart.), and Tulpay (*Clarisia racemosa* Ruiz & Pav.). They found that the interlocked grain negatively affected actual shear strength. Alves et al. (2013) used a non-destructive approach, namely the drill resistance, to estimate the shear strength of seven Brazilian tropical woods with densities varying from 650 to 1,150 kg/m^3. The results were validated thanks to good correlations (R^2 varying from 0.59 to 0.75) with shear tests performed in the longitudinal, tangential, and radial directions according to the Brazilian Standard NBR 7190 (1997). Ravenshorst et al. (2016) observed that the current shear strength values for high-density tropical hardwoods were very low compared to the values for softwoods, according to European strength class tables. As a solution approach, they investigated massaranduba wood, originating from Brazil, according to EN 408+A1 (2012). They found that the 5% value for the shear strength value of massaranduba was twice as high as the standardised value for strength class D70. Rodrigues et al. (2023) conducted similar investigations on Brazilian woods, considering the influence of growth rings position of wood. Wolensky et al. (2020) evaluated the accuracy of the relation proposed by NBR 7190 (1997) of shear strength along the grain to compression strength along the grain, based on 40 Brazilian wood species. The statistical analysis revealed that the geometric regression was the model of best fit. Yusoh et al. (2022) evaluated the effect of heat treatment on surface roughness, shear strength, and hardness of two tropical wood species from Malaysia, namely Batai (*Paraserianthes falcataria*) and Sesendok (*Endospermum malaccense*). In contrast to the untreated wood species, the heat-treated wood species exhibited lower values of shear strength. The shear of both species was adversely influenced by heat exposure. Ndong-Bidzo et al. (2021) performed shear compressive tests on various glue joints to understand the failure mode of glue-laminated timber made up of mixed tropical wood species during a 3-point bending behaviour. The shear specimens used were mortar-type masonry with two glue joints tested, according to EN 1052-3 (2003) specifications. These investigations have the potential to provide interesting information on the shear failure mode of two glue joints simultaneously. However, they need to be adapted and conducted on tropical solid woods from the Congo Basin.

As a major observation based on the literature review, it is difficult to find consistent information concerning the shear modelling of hardwood timbers from the Congo Basin. A traditional qualification process would be expensive and time-consuming since the number of timber species may be important. Moreover, the variability of that strength property was not considered in the available studies. The main objective of this study is to specify a preliminary qualification of Congo Basin timber species with regard to shear, in which the variability is considered. The research question is how the FCBA clustering specifications (FCBA Institute 2015) may be used to provide simple and useful information needed to facilitate the decision-making process while designing structures vis-à-vis the shear strength. Twelve (12) timber species with very different properties will be considered and assigned in the FCBA technological clusters. We assume that these clusters are homogeneous. That hypothesis will be justified in the data analysis section.

Table I.
Properties of 12 selected timber species of the Congo Basin at 12% moisture content (Paradis et al. 2015)

Selected timber species	Average density (kg/m^3)	Average flexural modulus of rupture (MOR) (MPa)	Average longitudinal modulus of elasticity (MOE) (MPa)
Abura (*Mitragyna ciliata*)	600	78	11.020
Ayous (*Triplochiton scleroxylon*)	430	52	7.260
Azobé (*Lophira alata*)	1,060	162	21.420
Bilinga (*Nauclea diderrichii*)	760	95	14.660
Dabema (*Piptadeniastrum africanum*)	700	98	15.190
Difou (*Morus mesozygia*)	840	143	18.490
Doussie (*Afzelia africana*)	800	124	17.020
Frake (*Terminalia superba*)	540	80	11.750
Movingui (*Distemonanthus benthamianus*)	730	116	14.740
Okan (*Cylicodiscus gabunensis*)	910	134	22.260
Padouk (*Pterocarpus soyauxii*)	790	116	15.870
Tali (*Erythrophleum ivorense*)	910	128	19.490

Material and Methods

Selection of timber species

The twelve species selected in this study are Abura (*Mitragyna ciliata*), Ayous (*Triplochiton scleroxylon*), Azobe (*Lophira alata*), Bilinga (*Nauclea diderrichii*), Dabema (*Piptadeniastrum africanum*), Difou (*Morus mesozygia*), Doussie (*Afzelia africana*), Frake (*Terminalia superba*), Movingui (*Distemonanthus benthamianus*), Okan (*Cylcodiscus gabunensis*), Padouk (*Pterocarpus soyauxii*), and Tali (*Erythrophleum ivorense*). Their strength properties at 12% Moisture Content (MC) are presented in table I (Paradis et al. 2015). Their longitudinal modulus of elasticity (MOE) values varied from 7,260 MPa to 22,060 MPa, and the flexural modulus of rupture (MOR) from 52 MPa to 162 MPa (Paradis et al. 2015). They present a wide range of use in several structural applications, such as panels, bridges, and flooring (Paradis et al. 2015).

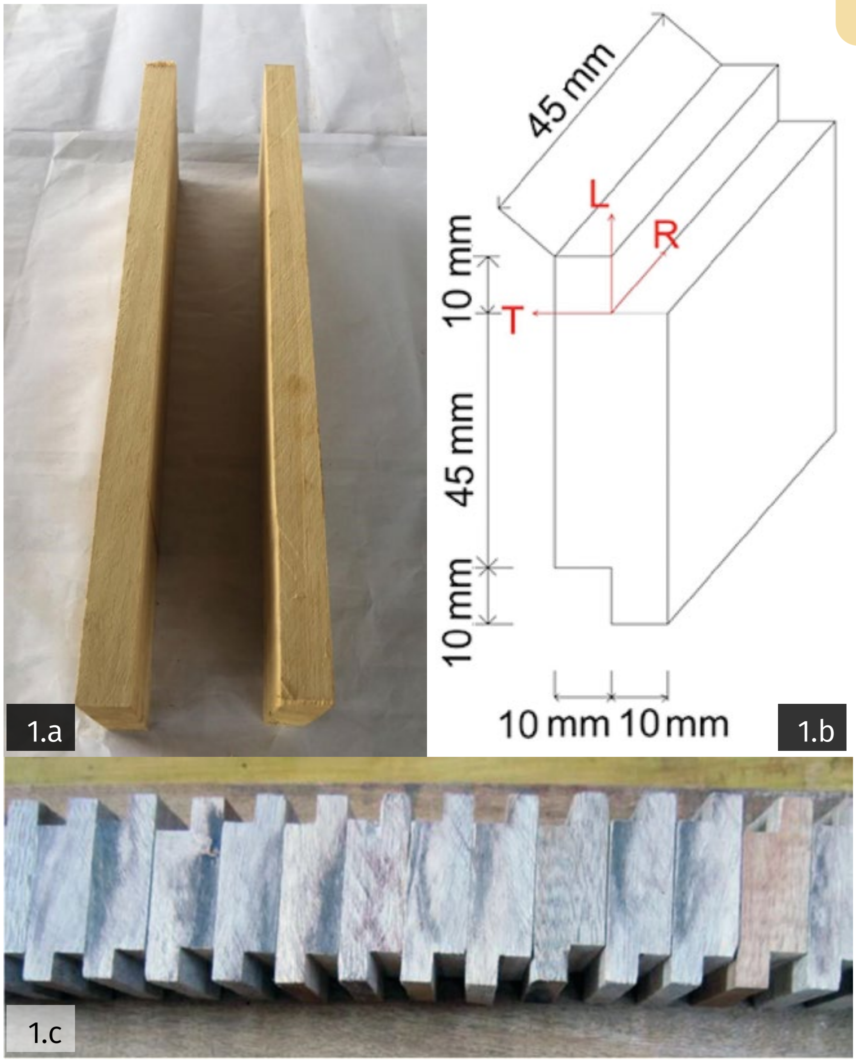

Figure 1.
Features of the shear specimens: 1.a A view of Tali (*Erythrophleum ivorense*) and Frake (*Terminalia superba*) wood lamellae; 1.b Dimensions and orthotropic directions of the specimens; 1.c Shear specimens manufactured using Abura (*Mitragyna ciliata*) species.

Preparation of shear test specimens

For each species, five quarter-sawn boards (length: 220 cm; width: 40 cm; thickness: 30 cm) were bought in different timber markets in the city of Yaoundé (Cameroon). They were composed of heartwood without defects and knots, and supplied with high MC. The quarter-sawn orientation of wood is useful to minimise the dimensional shrinkage during drying. General information about the trees of each species may be found in databases such as Prota4U[1]. Each board was planned and sawn into “lamellae” of 400 mm long and 150 mm wide. The thickness of the lamellae was around 26 mm. This operation allowed the wood to dry out for the first time. For each species, a batch of 10 lamellae (2 lamellae for a board) was stored in a climate chamber (temperature 20% ± 2% °C and relative humidity 65% ± 5%) for three months. Under these conditions, the MC of the wood at hygroscopic equilibrium stabilised at around 12%. Before manufacturing the test specimens, the wood was planned and the final average thickness was around 20 mm. For each board, two shear specimens were manufactured. The features of the specimen are illustrated in figure 1. The shape of the specimens was designed to enable a self-aligning seat, ensuring uniform lateral distribution of the load. Before carrying out the shear test, the dimensions and mass of each specimen were measured. This enabled us to deduce their density. At the end of the tests, each broken specimen was stored in an oven at 105 °C, until the corresponding mass stabilised. That step enabled us to determine the moisture content of the specimens corresponding to their ultimate shear strength.

Shear test

A shear stress parallel to grain was applied (figure 2), using a compressive load, in the solid wood (specimen) at a constant speed of 0.6 mm/min until failure occurs. The testing procedures were very close to those described in the EN 392 (1995) standard. They are similar to those specified by the NBR 7190 standard (1997) and the Nord American ASTM standard (D143). The NBR 7190 standard was successfully used by Wolensky et al. (2020) to assess the shear strength of Brazilian hardwood timbers. The ultimate shear strength f_v was calculated according to equation 1:

[1] www.prota4u.org

Bois et Forêts des Tropiques – ISSN: L-0006-579X
Volume 360 – 2nd quarter – June 2024 – p. 27-40

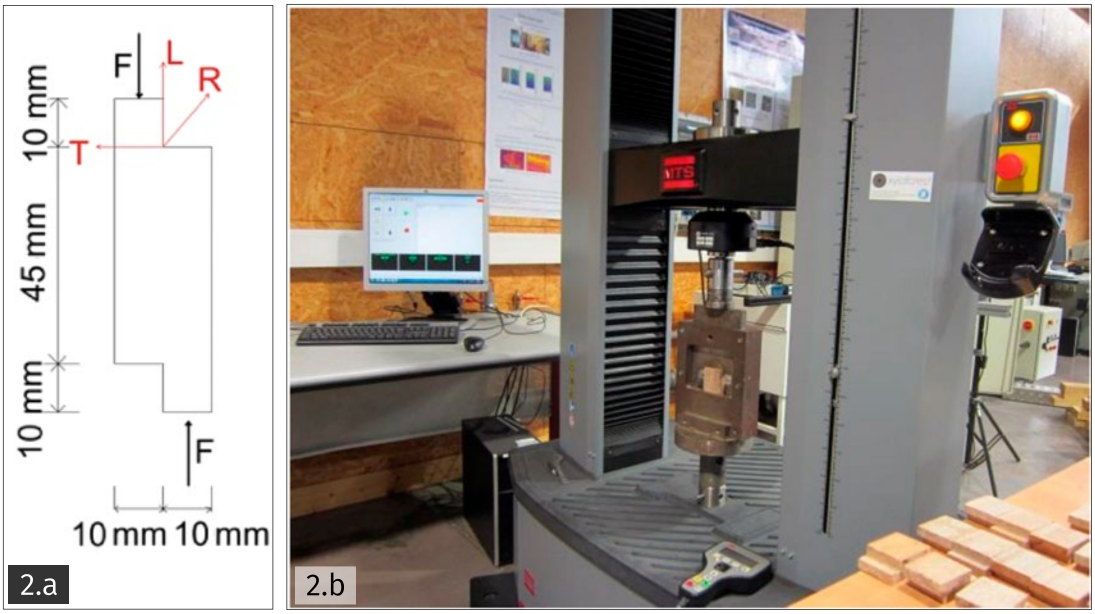

Figure 2.
Principle of the shear compressive test and sample device. 2.a Sample used for the shear compressive test and related loading condition; 2.b Shear compressive test device.
Photos O. Niapi.

$$f_v = k_v \frac{F_u}{A} \text{ (in N/mm}^2\text{)} \qquad \text{(equation 1)}$$

where F_u is the ultimate load (in N), A is the sheared area (in mm²), K_v is the correction scale factor (equation 2):

$$K_v = 0.78 + 0.0044t \qquad \text{(equation 2)}$$

where t is the thickness (in mm). Figure 2 illustrates the shear test device and the loading conditions.

Assignment of timber species into FCBA clusters

The average density of each timber species was estimated, making it possible to assign each species to a specific FCBA timber cluster (FCBA Institute 2015). We recall that the specifications enabled an organisation of the hardwood timber species into several clusters, among which: “very light” (230-500 kg/m³), “light” (500-650 kg/m³), “medium heavy” (650-865 kg/m³), and “heavy” (865-1,000 kg/m³). Hardwood timber species clustering is an appropriate tool to simplify the production of technical information such as shear strength and facilitate a decision-making process while designing wood structures.

Analysis of variance

A one-factor analysis of variance (ANOVA) test at a 5% significance level was carried out to assess the overall significant difference between the means of the shear strength within the timber species and the clusters. Two hypotheses were considered: H_0 (the means are equal (null hypothesis)); H_1 (the means are different). By ANOVA formulation, a p-value (p probability) lower than the adopted significance level (0.05) implies that the average values of the shear strength are statistically different, or equivalent otherwise (p-value ≥ 0.05). To identify where the differences between the groups lie, a Tukey HSD (Honestly Significance Difference) test was carried out to determine which means are different, with a significance level of 0.05. The ANOVA and Tukey HSD tests were computed thanks to the MINITAB 16 software.

Identification of the probabilistic distribution of the shear strength

The Goodness of Fit (GOF) test was performed to specify the statistical distribution of the shear strength, thanks to the MINITAB 16 software. There is a wide range of tests available in the literature to determine whether a sample could have been drawn from a specific distribution. Among them, we used the Anderson-Darling (AD) for the following reasons (Romeu 2003): (1) the ability to detect variations in the probability distribution’s overall shape; (2) a good adaptation for both small and large samples; (3) the use of the specific distribution in calculating critical values (CD). This has the advantage of allowing a more sensitive test. Moreover, it is widely used and may be considered as an alternative to the chi-square and Kolmogorov-Smirnov GOF tests. The AD statistic is (equation 3):

$$AD = -n + \sum_{i=1}^{i=n} \frac{1-2i}{n} \left[Ln\left(F\left(Y_i\right)\right) + Ln\left(1 - F\left(Y_{(N+1-i)}\right)\right) \right] \qquad \text{(equation 3)}$$

where F is the assumed distribution; Y_i is the ith sorted, standardised sample value; n is the sample size. The null hypothesis, which states that “the data follow a specified distribution,” is then rejected at a significance level of 0.05 if the AD statistic is greater than the critical value CD. The CD value is, in the case of normal distribution, given by equation (4):

$$CD = \frac{0.752}{1 + \frac{0.75}{n} + \frac{2.25}{n^2}} \quad \text{(equation 4)}$$

Five probability distributions were considered: normal, log-normal, 3-parameter Weibull, exponential, and 2-parameter Weibull (equations 5-9). They can be used for modelling the wood properties (de Melo et al. 2000).

- Normal distribution (equation 5):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2}\right) \quad \text{(equation 5)}$$

where μ is the mean and σ the standard deviation.

- Log-normal distribution (equation 6):

$$f(x) = \frac{1}{S\sqrt{2\pi}} \exp\left(\frac{-(Ln(x)-M)^2}{2S^2}\right) \quad \text{(equation 6)}$$

where *M* is the mean of *Ln(x)* and *S* the standard deviation of *Ln(x)*.

- 3-parameter Weibull distribution (equation 7):

$$f(x) = \frac{m}{w}\left(\frac{x-a}{w}\right)^{m-1} \exp\left(-\left(\frac{x-a}{w}\right)^m\right) \quad \text{(equation 7)}$$

where *a* is the location parameter, *m* is the shape parameter, *w* is the scale parameter.

- Exponential distribution (equation 8):

$$f(x) = \lambda \exp(-\lambda x)\, if\, x \geq 0 ; f(x) = 0\, if\, x < 0 \quad \text{(equation 8)}$$

where λ is the rate parameter.

- 2-parameter Weibull distribution (equation 9):

$$f(x) = \frac{m}{w}\left(\frac{x}{w}\right)^{m-1} \exp\left(-\left(\frac{x}{w}\right)^m\right) \quad \text{(equation 9)}$$

where *m* is shape parameter, *w* is scale parameter.

Results

Shear strength of the timber species

The shear strength of the 12-timber species globally ranged from 5.68 MPa (the minimum value) to 23.88 MPa (the maximum value), with a mean of 13.21 MPa and a standard deviation of 4.30 MPa. Figures 3, 4, and 5, respectively, show the post-test image of some specimens, the plot of the shear strength of the specimens versus wood density at around 12% MC, and the plot of the average shear strength versus average wood density of each specimen. Table II displays experimentally obtained mean values for the selected hardwood species. It shows that the best estimation of the shear strength is obtained by using the geometric regression model (R^2 = 0.74) (figure 4). The linear, logarithmic, polynomial, and exponential models underestimate the R^2 coefficient (table III). Such a trend is confirmed while estimating the mean shear strength value by using the mean density of the timber species (R^2 = 0.81) (figure 5). Results of the one-factor ANOVA test are presented in table IV.

Figure 3.
Post-test image of two specimens of Abura (*Mitragyna ciliata*) wood.

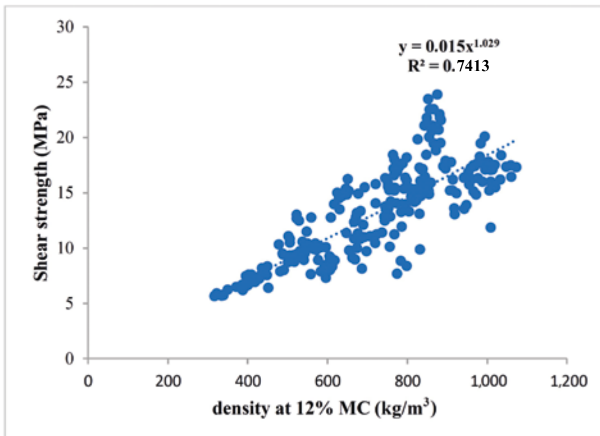

Figure 4.
Plot of the shear strength versus wood density at 12% moisture content of 12 selected timber species of the Congo Basin.

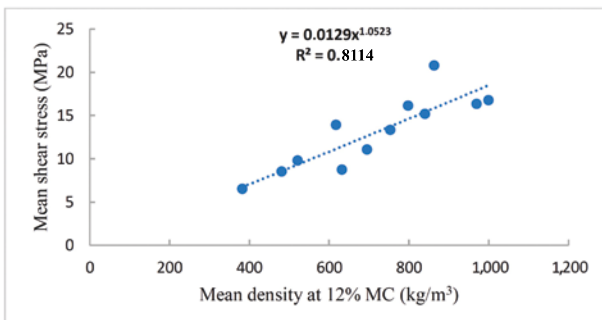

Figure 5.
Plot of the average shear strength versus average wood density at 12% moisture content.

According to the null hypothesis, the means of the shear strength of the timber species are all equal or equivalent. The p-value is less than the significance level of 0.05. We can therefore reject the null hypothesis and conclude that the shear strength of the timber species presents significantly different trends.

Clustering and probabilistic modelling of the shear strength

Results of the assignment procedure showed that the 12-timber species can be organised in four clusters, labelled 1 to 4: cluster 1 (very light hardwoods): Ayous, Frake; cluster 2 (light hardwoods): Abura, Movingui, and Dabema; cluster 3 (medium heavy hardwoods): Difou, Bilinga,

Table II.
Mean strength values at 12% moisture content for 12 selected timber species of the Congo Basin.

Selected timber species	Cluster	Density (kg/m³)		Experimental values of Shear strength (MPa)		Bibliographical values	
		Mean	Standard deviation	Mean	Standard deviation	Values (MPa)	References
Abura (*Mitragyna ciliata*)	Cluster 2	521	28	9.83	0.89	8-9	Nyunai Nyemb (2011)
Ayous (*Triplochiton scleroxylon*)	Cluster 1	383	37	6.56	0.57	3-8 6.8	Bosu and Krampah (2005) Green et al. (1999)
Azobé (*Lophira alata*)	Cluster 4	1,000	49	16.78	1.02	-	-
Bilinga (*Nauclea diderrichii*)	Cluster 3	841	37	15.18	1.18	8.5 - 17	Oppuni-Frimpong and Oppuni-Frimpong (2012)
Dabema (*Piptadeniastrum africanum*)	Cluster 2	617	55	13.95	1.48	7 - 18	Takofou (2008)
Difou (*Morus mesozygia*)	Cluster 3	798	29	16.13	1.62	-	-
Doussie (*Afzelia africana*)	Cluster 3	753	53	13.33	2.02	7.5 - 14	Gérard and Louppe (2011)
Frake (*Terminalia superba*)	Cluster 1	481	63	8.57	1.21	4.5 - 10 9.7	Sosef et al. (1995) Green et al. (1999)
Movingui (*Distemonanthus benthamianus*)	Cluster 2	632	73	8.77	0.81	12.5 - 14.5	Owusu and Loupe (2012)
Okan (*Cylicodiscus gabunensis*)	Cluster 4	866	17	20.81	1.82	8-22	Ayarkwa and Owusu (2008)
Padouk (*Pterocarpus soyauxii*)	Cluster 3	695	34	11.10	1.45	-	-
Tali (*Erythrophleum ivorense*)	Cluster 4	970	26	16.35	2.04	-	-

Table III.
Regression models for the shear strength estimation.

Regression models	Equation	R^2
Linear	$0.018x + 0.08$	0.66
Geometric	$0.015x^{1.029}$	0.74
Logarithmic	$12.044Ln(x) - 65.435$	0.67
Polynomial	$-10^{-5}x^2 + 0.0378x - 6.1694$	0.68
Exponential	$4.135e^{0.0015x}$	0.71

x: density of the specimen at 12% moisture content.

Table IV.
Results of the ANOVA for the sample sets.

Source	DF	SS	MS	F value	p value
Factor	11	3,892.83	353.89	177.32	0.000
Error	221	441.06	2.00		
Total	**232**	**4,333.89**			

DF: degrees of freedom; SS: sum of squares; MS: mean squares.

Table V.
Characteristics of the shear clusters.

Clusters	Density (kg/m³)		Shear strength (MPa)		Weibull parameters	5th Characteristic value (MPa)
	Mean	Standard deviation	Mean	Standard deviation		
Cluster 1 (very light species): Ayous (*Triplochiton scleroxylon*) Frake (*Terminalia superba*)	432	71.4	7.42	1.37	Shape: 1.153 Scale: 1.833 Threshold: 5.665	5.80
Cluster 2 (light species): Abura (*Mitragyna cyliata*) Movingui (*Distemonanthus benthamianus*) Dabema (*Piptadeniastrum africanum*)	593	73	10.94	2.55	Shape: 1.450 Scale: 4.052 Threshold: 7.258	7.78
Cluster 3 (medium heavy species): Bilinga (*Nauclea diderrichii*) Doussie (*Afzelia africana*) Padouk (*Pterocarpus soyauxii*) Difou (*Morus mesozygia*)	777	66	14.14	2.44	Shape: 7.772 Scale: 16.67 Threshold: -1.510	9.87
Cluster 4 (heavy species): Azobe (*Lophira alata*) Tali (*Erythrophleum ivorense*) Okan (*Cylicodiscus gabunensis*)	941	69	18.11	2.65	Shape: 3.052 Scale: 8.273 Threshold: 10.73	13.86

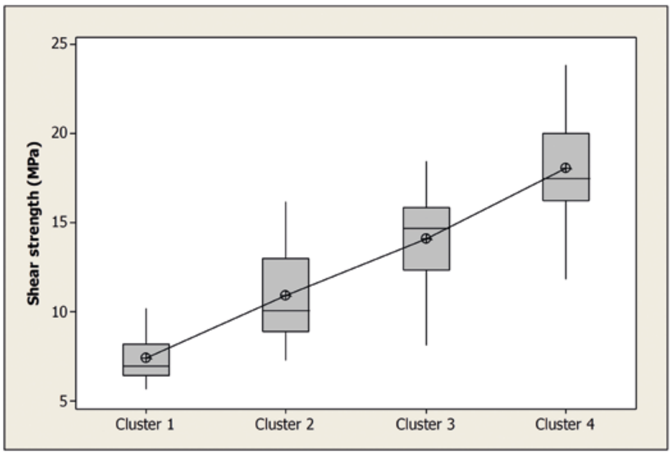

Figure 6.
Box plots of the shear clusters. Cluster 1 (very light species): Ayous (*Triplochiton scleroxylon*), Frake (*Terminalia superba*). Cluster 2 (light species): Abura (*Mitragyna cyliata*), Movingui (*Distemonanthus benthamianus*), Dabema (*Piptadeniastrum africanum*). Cluster 3 (medium heavy species): Bilinga (*Nauclea diderrichii*), Doussie (*Afzelia africana*), Padouk (*Pterocarpus soyauxii*), Difou (*Morus mesozygia*). Cluster 4 (heavy species): Azobe (*Lophira alata*), Tali (*Erythrophleum ivorense*), Okan (*Cylicodiscus gabunensis*).

Padouk, and Doussie; cluster 4 (heavy hardwoods): Azobe, Tali, and Okan. The shear strength characteristics of these clusters are presented in table V. The shear strength means varied from 7.42 MPa (cluster 1) to 18.42 MPa (cluster 4). The box plots of the shear clusters are illustrated in figure 6. The ANOVA resulted in a p-value less than 0.05 (table VI). Thus, the null hypothesis "the shear strength means of the clusters are equal" was rejected. Practically, we can conclude that at least one the shear clusters is different from the others. The results of the Tukey HSD test revealed that each cluster is significantly different from the other cluster, with an

Table VI.
Results of the ANOVA for the shear clusters.

Source	DF	SS	MS	F value	p-value
Factor	3	2,900.30	966.77	167.95	0.000
Error	223	1,283.67	5.76		
Total	**226**	**4,183.98**			

DF: degrees of freedom; SS: sum of squares; MS: mean squares.

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error rate of 1.04%, less than the 5% significance level. Table VII shows the results of the GOF tests. In each cluster, the Weibull, log-normal, and normal distributions do not fit properly the experimental data. Indeed, the Weibull distribution is only accepted in cluster 3, while the log-normal is useful only in cluster 1. The normal distribution is accepted in clusters 3 and 4 and rejected in the other clusters. Such a trend was not observed concerning the 3-parameter Weibull distribution. That distribution fits experimental data well in each cluster (figure 7).

Table VII.
Results of the Anderson-Darling test.

Distribution	Cluster 1			Cluster 2			Cluster 3			Cluster 4		
	AD	p-value	Decision	AD	p-value	Decision	AD	p-value	Decision	AD	p-value	Decision
3-parameters Weibull	0.588	0.133	accepted	0.795	0.042	accepted	0.435	0.211	accepted	0.656	0.063	accepted
Weibull	1.626	< 0.010	rejected	2.431	< 0.010	rejected	0.457	> 0.250	accepted	1.258	< 0.010	rejected
Exponential	10.774	< 0.003	rejected	16.551	< 0.003	rejected	23.959	< 0.003	rejected	19.688	< 0.003	rejected
Normal	1.314	< 0.005	rejected	2.326	< 0.005	rejected	0.814	0.034	accepted	0.760	0.045	accepted
Lognormal	0.841	0.027	accepted	1.553	< 0.005	rejected	1.459	< 0.005	rejected	0.480	0.226	accepted

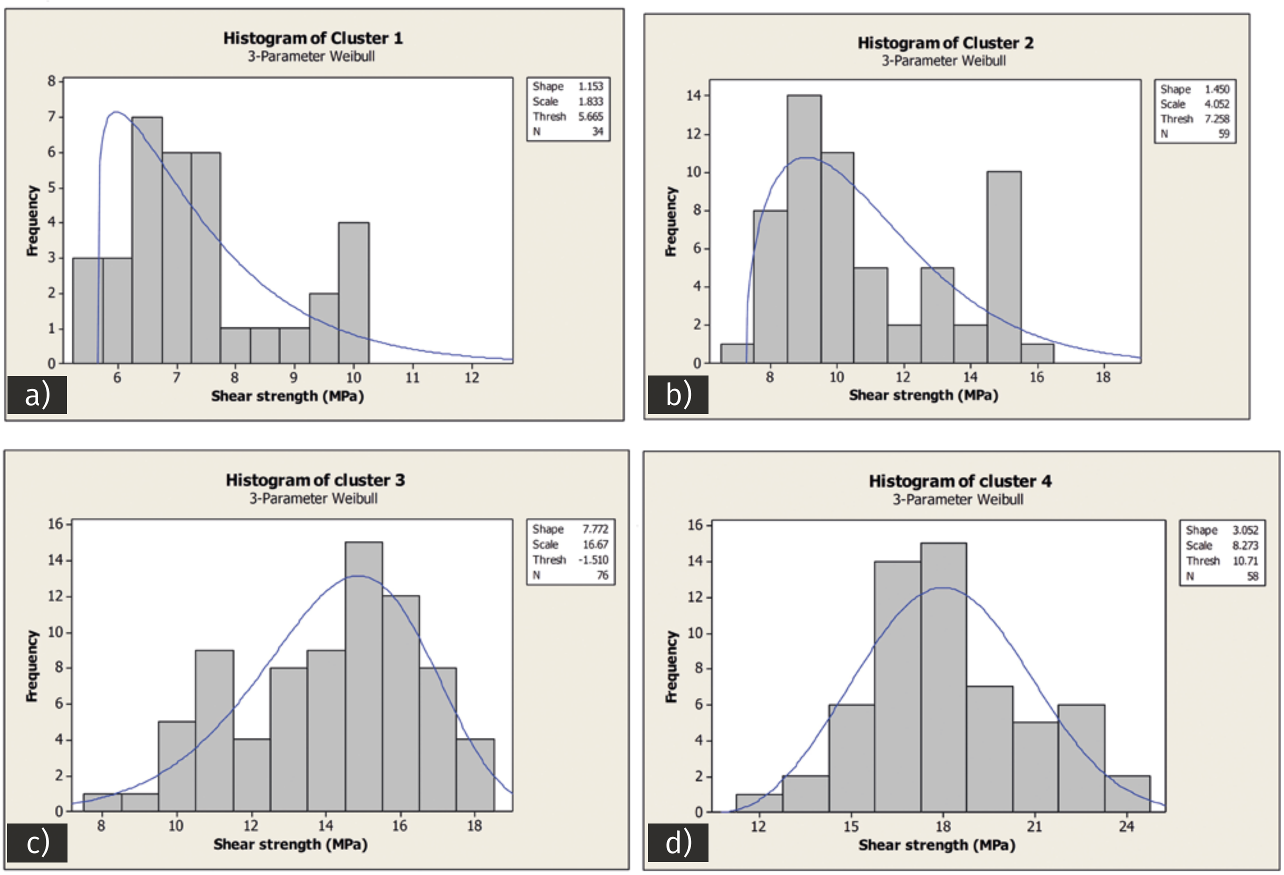

Figure 7.
Illustration of the statistical modelling of the shear strength with the histograms and 3-parameter Weibull modelling of: a) Cluster 1 (very light species): Ayous (*Triplochiton scleroxylon*), Frake (*Terminalia superba*). b) Cluster 2 (light species): Abura (*Mitragyna cyliata*), Movingui (*Distemonanthus benthamianus*), Dabema (*Piptadeniastrum africanum*). c) Cluster 3 (medium heavy species): Bilinga (*Nauclea diderrichii*), Doussie (*Afzelia africana*), Padouk (*Pterocarpus soyauxii*), Difou (*Morus mesozygia*). d) Cluster 4 (heavy species): Azobe (*Lophira alata*), Tali (*Erythrophleum ivorense*), Okan (*Cylicodiscus gabunensis*).

Discussion

The shear strength of wood must be considered in the design of wood structures (Hernandez and Almeida 2003). The shear strength parallel to grain is especially important since it is used to determine dimensions of wood structures. This study provides a preliminary qualification framework of the shear strength, adapted to the high diversity of timber species from the Congo Basin. Such a framework is specified according to two important points: the regression and the probabilistic modelling.

Concerning the first point, this study was conducted using a good diversity of the Congo Basin timbers, represented by 12 species with very different properties, from the least dense to the densest (table I). The difference between the species is confirmed by the ANOVA test. For each species (table IV). The comparison between our results and some available bibliographic values of the ultimate shear-strength parallel to the grain is presented in table II. These bibliographic values were provided while describing the properties of some timber species from the Congo Basin in the Prota4U database (Ayarkwa and Owusu 2008; Bosu and Krampah 2005; Doumenge and Séné 2012; Nyunai Nyemb 2011; Opuni-Frimpong and Opuni-Frimpong 2012; Owusu and Louppe 2012; Gérard and Louppe 2011; Sosef et al. 1995; Jiofack Tafokou 2008) and the Forest Products Laboratory (FPL) database of Madison (Green et al. 1999). Our experimental results are in good accordance with these bibliographic results. For instance, the average shear strength of a very light species such as Ayous wood (*T. scleroxylon*, density 383 kg/m^3 at 12% MC, cluster 1) was 6.56 MPa with a standard deviation of 0.57 MPa. Such a result is in accordance with the variation range from 3 to 8 MPa established by Bosu and Krampah (2005). It is also in accordance with the mean value of 6.8 MPa determined by Green et al. (1999). The average shear strength of Doussie (*A. Africana*, density 753 kg/m^3 at 12% MC, cluster 3), 13.33 MPa, is in accordance with the corresponding variation range 7.5-14 MPa, determined by Gérard and Louppe (2011). The global and successful comparison with bibliographic values is an argument for the validation of our experimental results.

The geometric regression provided the most adequate estimation of the shear strength of the timber species (table III). More precisely, that model explained 74% of the total variation of the shear strength (while considering individual specimens) and 81% of the average shear strength variation. Similar results were obtained by Ong (1988) and Green et al. (1999) while investigating the prediction of the shear strength of Malaysian timbers and some hardwood timbers from the Congo Basin at 12% MC, respectively. Ong (1988) found that the proportion of variation explained by the quadratic regression equations, as indicated by the value of R^2, for small clear specimens, was 0.75. However, the other regression models were not tested by these authors. Green et al. (1999) established that the shear strength parallel to the grain of hardwood timbers is correlated with their specific density at 12% MC according to equation 10:

$$\tau_{parallel} = 21{,}900\, G_{12}^{1.13} \quad \text{(equation 10)}$$

where $G_{12}^{1.13}$ is the specific gravity of timber species and $\tau_{parallel}$ is the shear strength parallel to the grain at 12% MC. The density ρ (kg/m^3) can be expressed as a function of the specific gravity G_m based on volume at H (%) MC according to equation 11 (Green et al. 1999):

$$\rho = 1{,}000\, G_m (1 + H) \quad \text{(equation 11)}$$

For H = 12%, we found that the shear strength $\tau_{parallel}$ is correlated with the specific gravity $G_{12}^{1.0523}$ according to equation 12:

$$\tau_{parallel} = 16{,}615\, G_{12}^{1.0523} \quad \text{(equation 12)}$$

One can notice that our results (equation 12) present some similarity with the Madison FPL Madison approach concerning the prediction of the shear strength (equation 10) at 12% MC. We recall that the FPL did not provide a regression coefficient. The differences among the coefficients of these equations may be explained by the high number of timber species investigated by the FPL.

The statistical analysis conducted by Wolenski et al. (2020) revealed that the geometric model provides the best fit for the prevision of the shear strength of Brazilian timbers. Therefore, in practical terms, the geometric regression models obtained in our study and illustrated in figures 4 and 5 can be considered as reference relations that may be successfully used to predict the shear strength by measuring the density of Congo Basin hardwoods. The estimated strength values from these regression equations will enable acceptable comparisons between species (even those that have not yet been investigated) to be made and provide fast and reasonably reliable basic data. Nevertheless, one should always notice that individual species should be tested by a strength testing machine whenever possible, so as to provide more accurate and complete information.

The second point deals with the specification of design parameters, such as the characteristic values. As a prerequisite, one needs to identify the proper probabilistic distribution model for the shear strength. It can be noticed in table VII that the exponential distribution is rejected in each cluster, while the acceptability of Weibull, normal, and log-normal distributions is neither consistent nor stable. The 3-parameter Weibull distribution is better suited to describe the shear failure in each cluster. Hence, all the shear failure of the Congo Basin hardwoods can be modelled by the 3-parameter Weibull distribution, making the model more straightforward. A similar result was obtained by Talla et al. (2005) while analysing the statistical model of *Rafia vinifera L.* (Arecacea), a bamboo species. Such a distribution can be successfully used in forestry applications (Green et al. 1994). The corresponding parameters of that distribution are presented in table V. One can also notice the characteristic values of the shear strength in table V. They are respectively 5.80 MPa (cluster 1), 7.78 MPa (cluster 2), 9.87 MPa (cluster 3) and 13.86 MPa (cluster 4). Although very light species such as Ayous wood and Frake wood (cluster 1) are not generally used for structural applications, their characteristic shear strength values may be used as threshold values in the decision-making process. These values will be useful for the shear design and reliable specifications of wood-based products from the Congo Basin. In a given cluster, different timber species may be used interchangeably without decreasing the quality of the product, specified in this study by the 5th characteristic values. The clustering approach should make it possible to simplify the production of technical information concerning the corresponding timber species. This result constitutes an improvement of the existing information on the shear strength of timber from the Congo Basin at the material scale.

Results of this study may facilitate the decision-making process while designing structural wood-based components, such as glulam and blockboards, using timber species from the Congo Basin. Within a given cluster, several timber species may be interchangeably used without decreasing the quality and integrity of the product. This is an important point concerning the preservation of endangered or over exploited timber species. The results may also be used to improve some tropical databases, such as Tropix 7.5.1, since each timber species may be attached to one quality specification (cluster). They also draw the possibility of reducing sampling costs while investigating the mechanical features of tropical timbers from the Congo Basin. However, their consolidation and implementation will need further investigations by considering more timber species.

Conclusion

The main objective of this study was to specify a preliminary qualification of Congo Basin timber species with regard to shear, in which the variability is considered. The reduction of the variability of that property is a major challenge in construction applications in which similar trends of resistance may be needed. To reach such a goal, 12-timber species with very different properties, from the least dense to the densest, were considered. Their shear strength was determined experimentally at 12% MC, based on European standards specification, at the scale of the wood material. They were derived from clear and defect free specimens. In the first step of our study, we showed that the prediction of the shear strength can be modelled properly using a geometric regression. A similar prevision trend was observed concerning Malaysian timber species. In the second step of our study, we showed that these species may be assigned to four distinct technological clusters, defined by their density range: “very light”, “light”, “medium heavy”, and “heavy”. The difference between clusters was confirmed by the Tukey HSD test. As an effort to develop design stresses aiming at facilitating a decision-making process, the relative Goodness of Fit of five shear strength distributions (normal, log-normal, exponential, 2-parameter Weibull, and 3-parameter Weibull) that are used in wood-related applications was evaluated. The results showed that the three parameter Weibull distribution is well suited compared to the other distributions. The findings of this study provide a new perspective on the various levels of performance with regard to shear, which should be considered when using tropical timber species from the Congo Basin. Potential applications may concern reliable and interchangeable uses in the construction industry and sampling costs reduction for potential testing of structural timbers.

Further research will address the acceptability and implementation of these results by wood industry operators in the African timber sector. More timber species need to be considered to consolidate our results. The specification of the influence of the orthotropic directions of wood, as well as the influence of moisture content on the shear strength, will be needed in order to enrich our results. We also intend to consolidate our results by investigating other shear testing procedures.

Acknowledgements
The authors acknowledge the support received from the Ministry of Higher Education of Cameroon. Many thanks are owed to the sawmills of the Centre Region of Yaoundé in Cameroon for their support in sawing and planning the wood planks. We also thank the Associate Editor and the reviewers for their suggestions to improve the paper.

Funding
The research presented in this article was primarily funded by the lead author, M. Olivier Ndiapi. We also gratefully acknowledge the support provided by the Ministry of Higher Education in Cameroon.

Data access
The data used in this article is openly available on Zenodo, a trusted repository for research outputs. Please cite the dataset using the following citattion and by citing this article : Ndiapi O., 2024. Shear strength characterization and statistical modelling of 12 hardwood timber species from the Congo Basin [Data set]. Zenodo. https://doi.org/10.5281/zenodo.11094816

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