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Cross-laminated timber: A state-of-the-art review towards a proposed structural analysis strategy

BE Boulle, JE van der Merwe, CP Roth

Cross-laminated timber (CLT) has experienced growing global popularity in recent years, extending to South Africa with the adoption of SANS 8892 (2020), which allows for local manufacturing of performance-rated CLT. However, this standard requires all locally produced CLT layups to undergo extensive mechanical verification to determine strength and stiffness properties. Analytical methods have proven relatively accurate in predicting the out-of-plane mechanical properties of CLT. Incorporating these methods into design equations can aid in the structural design and sizing of CLT elements. The currently proposed prEN 1995-1-1 (2023) contains design factors specific to CLT, largely common with sawn timber. Adopting such an approach would simplify CLT design in South Africa, using established partial factors, as is the case for plywood. Resistance equations are therefore proposed using existing partial factors for sawn timber design in SANS 10163-1 (2003), incorporating Timoshenko beam theory calculations for bending and shear stresses in CLT. However, the material resistance factor value of 0.68 proposed for sawn timber may be overly conservative due to CLT's inherent load-sharing behaviour. Using the methods outlined by Pagel (2019) and variability results of South African pine-only CLT obtained by Jacobs (2023), an average resistance factor of 0.79 was determined.

Keywords: Cross-laminated timber, shear analogy method, Timoshenko, gamma method, resistance factor

INTRODUCTION

With an ever-increasing awareness of the environmental impacts of human development, mass timber construction has emerged as a greener alternative to conventional, typically mineral-based building materials such as reinforced concrete. CLT is an engineered wood product (EWP) consisting of orthogonally alternating timber boards (lamellae) that are adhesively bonded to form a panel. This composition gives CLT an improved degree of dimensional stability that is more akin to that of reinforced concrete (Mohammad *et al* 2012), as well as enhanced load-sharing capabilities, reducing the effect of material variability (Schickhofer *et al* 2016). These advantages result in CLT being used primarily in wall and floor panels. CLT has experienced a substantial increase in popularity since its introduction, and growth is expected to continue in the coming years. This has resulted in various regions, such as the United States, Canada, and Japan, developing local standards to accommodate CLT-inclusive construction (Kuzinski *et al* 2022).

A modified version of ANSI/APA PRG 320 (2017) was adopted as SANS 8892 (2020) to provide requirements for performance-rated CLT, allowing code-compliant CLT manufacturing in South Africa. The code sets requirements for aspects such as fabrication, performance, qualification, and quality assurance. A table with the required characteristic mechanical properties of lamellae used in various CLT layups is included with various design values. However, according to SANS 8892 (2020), CLT layups manufactured in South Africa should be treated as custom layups, as specified in ANSI/APA PRG 320 (2017). This requires all unique layups to undergo mechanical testing to determine characteristic properties, potentially limiting the willingness of local manufacturers to supply a broader range of layup options.

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However, analytical methods exist that, in the literature, have proven relatively accurate in predicting the out-of-plane behaviour of CLT. These methods account for shear deformation acting perpendicular to the grain (rolling shear) in the transverse lamellae in the CLT. These deformations cannot be reasonably ignored due to their impact on bending performance (Aicher *et al* 2016). Such modelling would facilitate the incorporation of design principles from other standards, such as SANS 10163-1 (2003) and SANS 1707-1 (2022) for eucalyptus hardwood-inclusive layups. While performance testing is vital to ensure the quality manufacturing of CLT, analytical method-inclusive design standards may provide the incentive for more customised CLT layup options.

While SANS 8892 (2020) is helpful to the local timber construction industry by allowing standardised manufacturing of CLT in South Africa, no provisions concerning CLT structural design are stipulated. This means prospective clients and contractors wishing to utilise CLT in their regional projects may require their engineers to use international standards or handbooks for crucial design calculations such as member sizing and capacity. Alternatively, this task can be outsourced to engineers based abroad, such as in Europe, where CLT has seen far more extensive usage (Kuzinski *et al* 2022). Such compromises may disincentivise more extensive adoption of CLT in South Africa. Developing a more locally-informed guide to CLT design may allow for more optimised design solutions and provide a more accessible framework for CLT-inclusive construction.

This study aims to recommend procedures for the structural design of CLT elements loaded out-of-plane using South African timber design principles. To this end, the study has the following objectives:

- Provide an overview of analytical methods that estimate the out-of-plane response of CLT and compare their accuracy using results published in the literature.
- Compare and discuss the respective partial factors used in the South African and European timber design standards and propose resistance equations for CLT under out-of-plane bending.
- Explore material resistance factors for South African CLT using the coefficients of variation obtained by Jacobs (2023) for South African pine-only CLT.

ANALYTICAL METHODS

Despite having bi-directional properties, CLT elements are generally designed as beams rather than slabs when loaded out-of-plane. This simplification is justified by the typically limited width of CLT panels, which does not allow significant bending moment transfer to adjacent panels in the minor direction (Christovasilis *et al* 2016). However, shear deformation in CLT under out-of-plane loading needs to be considered, meaning that traditional Euler-Bernoulli beam theory cannot be applied directly to CLT elements (Li *et al* 2020). Although various beam theory adaptations have been presented in the literature to incorporate these shear deformations in their calculations, little experimental validation exists to date.

Timoshenko beam theory

An extension of Euler-Bernoulli beam theory, Timoshenko beam theory considers shear deformation in thick composite beams by considering the total deflection as the sum of the bending and shear deflection (Rahman *et al* 2020b). The effective bending stiffness (Equation 1) is the sum of the eigen stiffnesses and Steiner-terms for each layer, while the effective shear stiffness (Equation 2) is taken as the quotient of the sum of the local shear stiffnesses for each layer divided by a shear adjustment factor (Bogensperger *et al* 2012). The numbering scheme for the layers is visualised in Figure 1.

$$EI_{eff} = \sum_{i=1}^{n} \left(\frac{E_i \cdot b \cdot h_i^3}{12} + E_i \cdot A_i \cdot y_i^2 \right) \quad (1)$$

$$GA_{eff} = \sum_{i=1}^{n} \frac{G_i \cdot A_i}{\kappa} \quad (2)$$

Where: EI_{eff} is the effective bending stiffness of the cross-section (Nmm^2), n is the number of layers in the cross-section, E_i is the elastic modulus of layer i (MPa), b is the width of the cross section (mm), h_i is the thickness of layer i (mm), A_i is the cross-sectional area of layer i (mm^2), y_i is the distance from the centroid of layer i to the centroid of the cross-section (mm), GA_{eff} is the effective bending stiffness of the cross-section (N), G_i is the shear modulus of layer i (MPa), and κ is the shear adjustment factor.

The shear adjustment factor is layup dependent, as it considers layer thickness, elastic and shear moduli for each layer, as well as the effective bending stiffness of

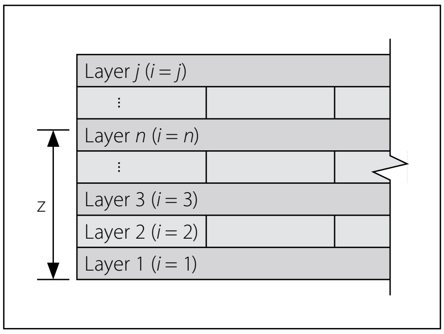

Figure 1 Layer numbering scheme for analytical method calculations

the entire layup, as shown in Equation 3 (Rahman *et al* 2020b). While the formula presented is relatively complex, values for the shear adjustment factor can be given in tabular form for common layups in the interest of more convenient design procedures, adopting the strategy of Bogensperger *et al* (2012).

$$\kappa = \sum_{i=1}^{n} \frac{G_i \cdot A_i}{(EI_{eff})^2} \cdot \int_0^{h_{tot}} \frac{[EQ(z)]^2}{G_j \cdot b} dz \quad (3)$$

Where: h_{tot} is the total thickness of the layup (mm), z is the position within the cross-section (mm), $EQ(z)$ is the product of the modulus of elasticity and the first moment of area with respect to z (Nmm), and G_j is the shear modulus of layer j (the layer in which z is located) (MPa).

The effective shear stiffness is subsequently incorporated into deflection calculations to account for shear deformation in the cross section. The total deflection is taken as the sum of the bending and shear deflection terms, the latter of which is the quotient of the bending moment divided by the effective shear stiffness. Equation 4 gives total deflection under a uniformly distributed load. The combination of the effective bending and shear stiffnesses can be transformed into an apparent bending stiffness (Equation 5), which is compatible with Euler-Bernoulli beam theory equations (Equation 4).

$$u_{max} = \frac{5 \cdot w \cdot L^4}{384 \cdot EI_{app}} = \frac{5 \cdot w \cdot L^4}{384 \cdot EI_{eff}} + \frac{w \cdot L^2}{8 \cdot GA_{eff}} \quad (4)$$

$$EI_{app} = \left(\frac{1}{EI_{eff}} + \frac{\lambda}{L^2 \cdot GA_{eff}} \right)^{-1} \quad (5)$$

Where: u_{max} is the maximum deflection (mm), w is the uniformly distributed load (N/mm), L is the span length (mm), EI_{app}

Table 1 Moment, deflection and apparent shear stiffness coefficient for some loading patterns

Load pattern	Moment equation	Moment coefficient λ_m	Deflection equation	Deflection coefficient λ_u	Apparent shear stiffness coefficient λ
Uniformly distributed load	$\frac{w \cdot L^2}{8}$	$\frac{1}{8}$	$\frac{5 \cdot w \cdot L^4}{384 + EI_{app}}$	$\frac{5}{384}$	$\frac{48}{5}$
Third-point loads	$\frac{P \cdot L}{3}$	$\frac{1}{3}$	$\frac{23 \cdot P \cdot L^3}{324 \cdot EI_{app}}$	$\frac{23}{324}$	$\frac{108}{23}$
Central-point loads	$\frac{P \cdot L}{4}$	$\frac{1}{4}$	$\frac{P \cdot L^3}{48 \cdot EI_{app}}$	$\frac{1}{48}$	12

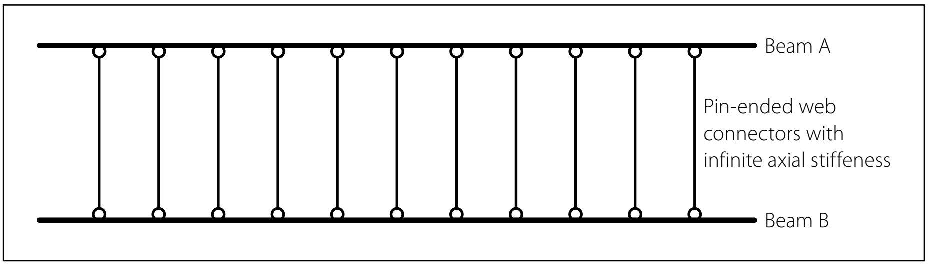

Figure 2 Virtual beam theory of shear analogy method (adapted from Karacabeyli & Gagnon 2019)

is the apparent bending stiffness (Nmm^2), and λ is the apparent shear stiffness coefficient.

The value for the apparent shear stiffness coefficient is dependent on the loading patterns applied to the beam and is taken as the quotient of the moment coefficient divided by the deflection coefficient (Equation 6). Values for these coefficients for uniformly distributed loads, third-point loading, and central point loading are given in Table 1.

$$\lambda = \frac{\lambda_m}{\lambda_u} \tag{6}$$

Where: λ_m is the moment coefficient and λ_u is the deflection coefficient.

Modified gamma method

Adapted from the method of mechanically jointed beams defined in EN 1995-1-1 (2008), the modified gamma method is the most popular method of CLT property estimation in Europe (Christovasilis *et al* 2016). Instead of taking shear deformation into account using an effective shear stiffness term, the rolling modulus values of the transverse layers are included in the calculation of the modified gamma factor for the outer layers (Equation 7). The modified gamma factor is added to the Steiner terms for each layer in the calculation of the effective bending stiffness (Equation 8), which is essentially the apparent bending stiffness. It should be noted that the modified gamma values for the transverse layers are taken as zero and is taken as one for the middle layer of a five-layer system.

$$\gamma_i = \left(1 + \frac{\pi^2 \cdot E_i \cdot A_i \cdot h_k}{L^2 \cdot G_{R,k} \cdot b}\right)^{-1} \quad (i = 1, n) \tag{7}$$

$$EI_{eff} = EI_{app} = \sum_{i=1}^{n} \left(\frac{E_i \cdot b \cdot h_i^3}{12} + \gamma_i \cdot E_i \cdot A_i \cdot y_i^2\right) \tag{8}$$

Where: γ_i is the modified gamma factor, h_k is the thickness of layer k (the transverse layer adjacent to layer i) (mm), and $G_{R,k}$ is the rolling shear modulus of layer k (MPa).

Moreover, the modified gamma factor calculation includes the effective length of the beam. Low modified gamma factors at short effective lengths lead to high calculated bending stresses and low calculated shear stresses. The Canadian CLT Handbook (Karacabeyli & Gagnon 2019), therefore, recommends the modified gamma method only be applied for longer span-to-depth ratios, ideally 30 or higher. Furthermore, the modified gamma method is only suited to three- and five-layer CLT layups, with further modifications being required for thicker layups (Christovasilis *et al* 2016).

Shear analogy method

The shear analogy method was developed by Kreuzinger (1999, as cited by Bogensperger *et al* 2012) and is a common method to estimate the out-of-plane flexural capacity of a CLT panel. It involves separating a multilayer cross section into two virtual beams, Beam A and Beam B, which are joined by pin-ended web connectors (Figure 2), effectively resulting in equal vertical deflection for both virtual beams at every point along the span (Karacabeyli & Gagnon 2019). The effective bending stiffnesses of Beam A (Equation 9) and Beam B (Equation 10) are taken as the sum of the eigen stiffnesses for each layer and the sum of the Steiner-terms for each layer, respectively.

$$EI_{eff,A} = \sum_{i=1}^{n} \frac{E_i \cdot b \cdot h_i^3}{12} \tag{9}$$

$$EI_{eff,B} = \sum_{i=1}^{n} E_i \cdot A_i \cdot y_i^2 \tag{10}$$

Where: $EI_{eff,A}$ is the effective bending stiffness of Beam A (Nmm^2), and $EI_{eff,B}$ is the effective bending stiffness of Beam B (Nmm^2).

The effective shear stiffness of Beam A is taken as infinite, while the effective shear stiffness of Beam B can be calculated using Equation 11 (Rahman *et al* 2020a).

$$GA_{eff,B} = a^2\left[\left(\frac{h_1}{2G_1 b}\right) + \left(\sum_{i=2}^{n-1} \frac{h_i}{G_i b}\right) + \left(\frac{h_n}{2G_n b}\right)\right]^{-1} \tag{11}$$

Where: $GA_{eff,B}$ is the effective shear stiffness of Beam B (N), and a is the distance between the centroids of the outer layers (mm).

Deflection is calculated using Euler-Bernoulli beam theory for Beam A, while Beam B considers the effective shear stiffness term. The total load is partitioned between Beam A and Beam B accordingly to ensure equal deflection (Equation 12).

$$u_{max} = \frac{5 \cdot w \cdot L^4}{384 \cdot EI_{app}} = \frac{5 \cdot w_A \cdot L^4}{384 \cdot EI_{eff,A}} = \frac{5 \cdot w_B \cdot L^4}{384 \cdot EI_{eff,B}} + \frac{w_B \cdot L^2}{8 \cdot GA_{eff,B}} \tag{12}$$

Where: w_A is the uniformly distributed load applied to Beam A (N/mm), and w_B is the uniformly distributed load applied to Beam B (N/mm).

Subsequently, the apparent bending stiffness using the shear analogy method can

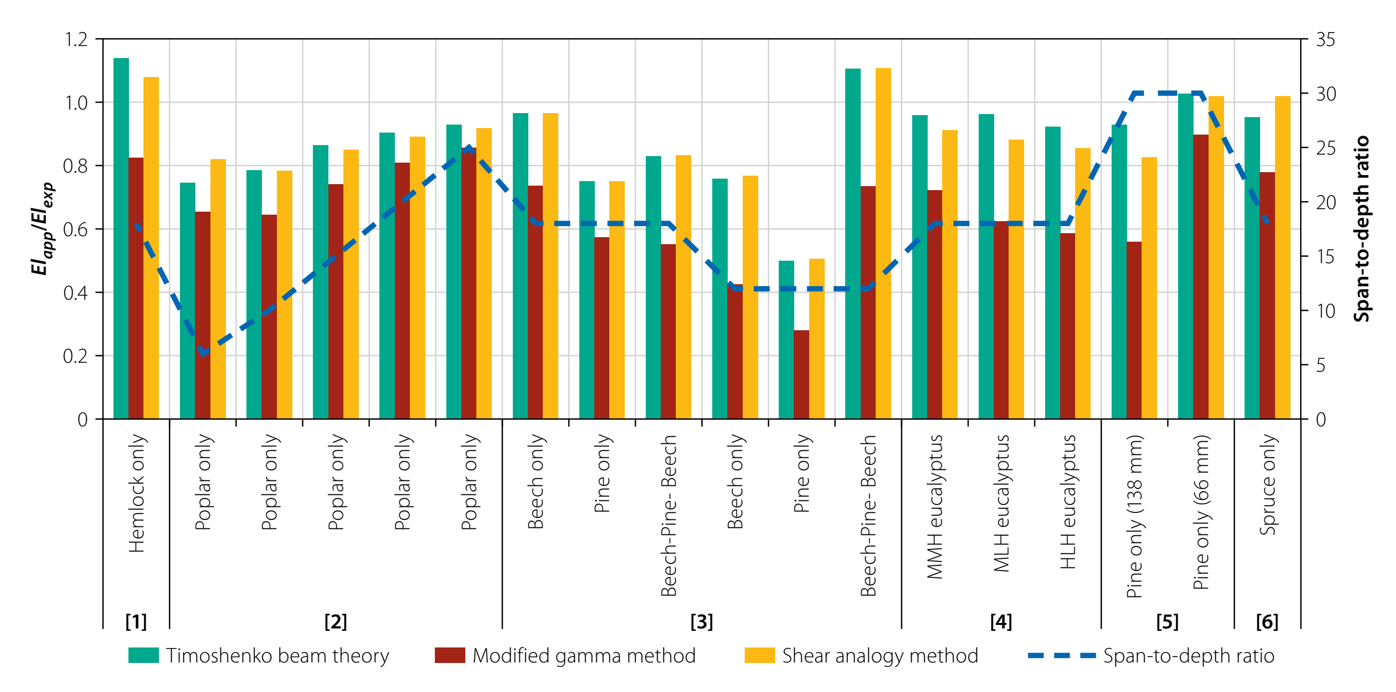

Figure 3 **Comparisons of analytically estimated apparent bending stiffnesses to experimental bending stiffnesses using input values from the literature**

be calculated using Equation 13. It should be noted that the apparent shear stiffness coefficient values are the same in the shear analogy method as in Timoshenko beam theory; therefore, the values provided in Table 1 are used.

$$EI_{app} = EI_{eff,A} + \left(\frac{1}{EI_{eff,B}} + \frac{\lambda}{L^2 \cdot GA_{eff,B}} \right)^{-1} \quad (13)$$

Method comparison

In most cases, out-of-plane CLT design is likely to be governed by serviceability aspects such as deflection (Karacabeyli & Gagnon 2019). Therefore, it is critical that the discussed methods can accurately predict the stiffness response of a CLT element by incorporating the local properties of the lamellae of which it is composed.

This section presents a comparison of Timoshenko beam theory, the modified gamma method, and the shear analogy method to experimental results found in the literature. Studies were searched for on Google Scholar using a variety of search terms. The studies included in the comparison were narrowed down to those included the parallel elastic modulus of the timber boards that were used to fabricate the CLT test specimens. Furthermore, the studies needed to include out-of-plane stiffness results, either reported directly as experimental bending stiffness (in Nmm²), or as an apparent modulus of elasticity, which could then be multiplied by the moment of inertia of the full cross section to calculate the experimental bending stiffness of the CLT specimen. Lastly, only test methods such as central- and third-point loading were considered to facilitate apparent bending stiffness calculations using the values provided in Table 1.

With respect to the perpendicular elastic modulus, as well as the parallel (planar) and perpendicular (rolling) shear modulus values, the following assumptions were made: the perpendicular elastic modulus was taken as one 30th of the parallel modulus (following the assumptions made in various studies, as well as in ANSI/APA PRG 320 (2017) and EN 338 (2016)), the planar shear modulus was taken as one 16th of the parallel elastic modulus (following the assumption made in SANS 10163-1 (2003)), and the rolling shear modulus was taken as one 10th of the planar shear modulus (as proposed in studies such as Fellmoser & Blaß (2004), Mestek *et al* (2008) and Bogensperger *et al* (2012)).

The accuracy of each method was determined with the ratio of the apparent bending stiffness, EI_{app}, and the experimental bending stiffness, EI_{exp}, obtained from the results of the study. Ultimately, the results from six studies were considered: Ruan *et al* (2019), Hematabadi *et al* (2020), Sciomenta *et al* (2021), Ettelaei *et al* (2022), Jacobs (2023) and Alabbad (2024). These are labelled from 1 to 6, respectively, in Figure 3 in the interest of legibility. While the limited scope of this comparison is acknowledged, studies that provide the properties of the lamellae and subsequent CLT panels are infrequent in the literature. Furthermore, all the studies considered investigated three-layer CLT layups, with studies on five-layer layups receiving comparatively minimal attention to date. Nevertheless, a wide range of span-to-depth ratios and layup configurations are included in the comparison, as shown in Figure 3.

Generally, the apparent bending stiffnesses calculated using the three analytical methods were lower than the experimental bending stiffness. The average ratios of the calculated apparent bending stiffness and the experimental bending stiffnesses for Timoshenko beam theory, the modified gamma method and the shear analogy method were 0.89, 0.67 and 0.88, respectively. Values calculated using the shear analogy method and Timoshenko beam theory were, in most cases, very similar and are deemed the two most accurate of the three methods, while the values obtained using the modified gamma method were noticeably lower than the other two methods.

STRUCTURAL DESIGN

One of the main differences between structural timber design codes is how each standard defines the various partial material and load factors. Each region has unique circumstances surrounding its timber industries, and local design factors largely reflect these. Effective development of CLT design standards ideally incorporates local material and safety factors as well as timber strength grades to determine characteristic strength values for various layups and more generalised CLT strength classes.

South African National Standard

SANS 10163-1 (2003) names six partial material factors and a resistance factor for structural timber design. These resistance factors, defined as γ_{m1} to γ_{m6} are factors for load duration, load sharing, stressed volume, moisture content, pressure treatment, and area stressed by connectors, respectively. However, only γ_{m1}, γ_{m2}, γ_{m3} and γ_{m5} are considered in calculating the ultimate values for tension, shear, and bending in individual members. Resistance factors γ_{m4} and γ_{m6} are only included in tension perpendicular to the grain and axial compression resistance calculations, respectively. In addition to a material resistance factor, these factors are typically applied as demonstrated in Equation 14. A similar procedure is followed to calculate moment resistance values.

$$F_{r,x} = f_{k,x} \cdot A_x \cdot \frac{\phi}{\Pi \gamma_{mx}} \tag{14}$$

Where: $F_{r,x}$ is the force resistance of property x (N), $f_{k,x}$ is the characteristic strength of property x (MPa), A_x is the applicable area for property x (mm^2), ϕ is the material resistance factor (ϕ = 0.68), and γ_{mx} are the applicable partial material factors for property x.

The formula for the load duration factor, γ_{m1}, includes load case-dependent factors for permanent and wind loads, as well as imposed loads (which are also dependent on load duration). The load-sharing factor, γ_{m2}, is typically taken as 1 in most cases, except in unique cases where some members are restrained to the same deflection with uniformly distributed loads with a spacing of less than 600 mm, where γ_{m2} is taken as 0.87. This factor may require further investigation in the context of CLT considering CLT's improved degree of load sharing between individual lamellae over sawn timber (Schickhofer *et al* 2016).

Length-dependent equations for the stressed volume factor, γ_{m3}, is given for both truss members and beams or girders. In the case of CLT, it might be reasonable to assume that the formula for beams and girders should be used for CLT elements. As for the pressure treatment factor, γ_{m5}, its relevance to CLT may require further investigation. This factor accounts for the use of water-borne treatment methods, such as preservatives or fire retardants. Since CLT consists of inner elements that would not be exposed to these treatments (unless applied before pressing), it is not immediately clear what factor might be relevant to CLT.

The resistance factor for timber, ϕ, is taken as 0.68. This factor accounts for the variability of timber as a building material, and the value of 0.68 is seemingly derived from the variability of sawn timber. CLT is known to possess a higher degree of load sharing which results in lower variation across mechanical properties. Therefore, a CLT-specific resistance factor is discussed later in this study.

Eurocode

Europe currently faces a similar issue as South Africa regarding its CLT code. EN 16351 (2021), like SANS 8892 (2020), is a manufacturing performance specification code rather than a CLT design code (Brandner *et al* 2024). EN 1995-1-1 (2008) does not provide any factors specific to CLT. However, this is set to change with the currently proposed prEN 1995-1-1 (2023). While this standard is yet to be adopted and is subject to change, the proposed standard includes various unique material factors and design considerations for CLT. Furthermore, prEN 1995-1-1 (2023) defines a strength class for CLT: CL24, based primarily on C24 grade softwood as prescribed in EN 338 (2016).

The two most prominent factors proposed in Eurocode 5 are for load duration and moisture content, k_{mod}, and a partial material resistance factor, γ_M. Additional k factors are included for specific properties where applicable. The application of these factors is shown in Equation 15. Values for k_{mod} for CLT range between 0.6 and 1.1 depending on load duration and are the same for both service classes 1 and 2. For CLT, γ_M is taken as 1.25 in prEN 1995-1-1 (2023), compared to 1.3 for regular sawn timber. However, the value for CLT seems to be open to modification in national annexes (Borgström & Fröbel 2019).

$$f_{d,x} = f_{k,x} \cdot \frac{k_{mod} \cdot \Pi k_x}{\gamma_M} \tag{15}$$

Where: $f_{d,x}$ is the design strength of property x (MPa), k_{mod} is the modification factor for duration of load and moisture content, k_x are the additional modification factors for property x, and γ_M is the partial material resistance factor.

In addition to the definition of safety factors, the most notable difference between Eurocode 5 and SANS 10163-1-1 (2003) is how design values are generally calculated in stresses, as opposed to forces and moments. Although this deviation in approach would have a seemingly insignificant effect when calculating resistance values for sawn timber sections, the impact on CLT calculations may be more apparent. The design philosophy of stress-based calculations used in Eurocode 5 could be considered more applicable to CLT given the existing equations currently proposed using analytical methods from the literature.

There are several k factors defined in prEN 1995-1-1 (2023) that are unique to CLT design. Firstly, a width reduction factor is defined for elements less than 600 mm wide but wider than the thickness of the panel. This factor appears to be relevant for cases where CLT is used as a beam, as CLT used for walls or floor panels is unlikely to drop below 600 mm wide. A factor for non-linear behaviour, $k_{r,pu}$, of 1.6 is applied to the design rolling shear stress value in cases of concentrated loads applied out-of-plane. A stress-spreading factor is applied for compressive stresses perpendicular to the grain, with values given as either one or by an equation with respect to the loaded area. Additional factors and provisions are provided for screw-reinforced CLT, CLT loaded in-plane and ribbed plates made from CLT and ribs, but these special cases are beyond the scope of this study.

EN 16351 (2021) defines two unique k factors: a statistical factor for finger joint compliance and a moisture deformation factor for swelling and shrinkage of lamellae during manufacturing. The adequacy of finger jointing in CLT in South Africa is addressed in the national annex to SANS 8892 (2020). The effect of moisture-related shrinkage and swelling on lamellae may differ from region to region and may warrant further, ideally localised, investigation.

Potential design equations

Both standards have different sets of variables that determine the partial material factors, with commonly shared considerations including load duration and moisture content (γ_{m1}, γ_{m4} and k_{mod}) as well as material variability (ϕ and λ_M). Otherwise, different variables are considered by both codes to determine highly case-dependent solutions, making representative comparisons difficult. In general, most of the partial factors applied to CLT according to prEN 1995-1-1 (2023) appear to be similar to or shared with regular sawn timber. Therefore, the use of proven

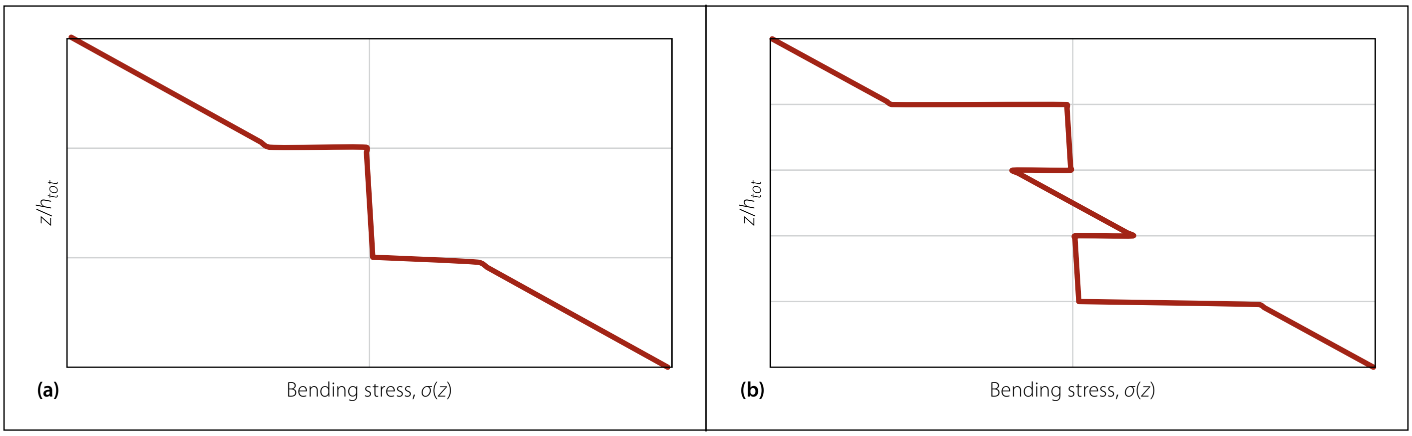

Figure 4 Major direction bending stress distributions in a) three-layer and b) five-layer CLT cross sections

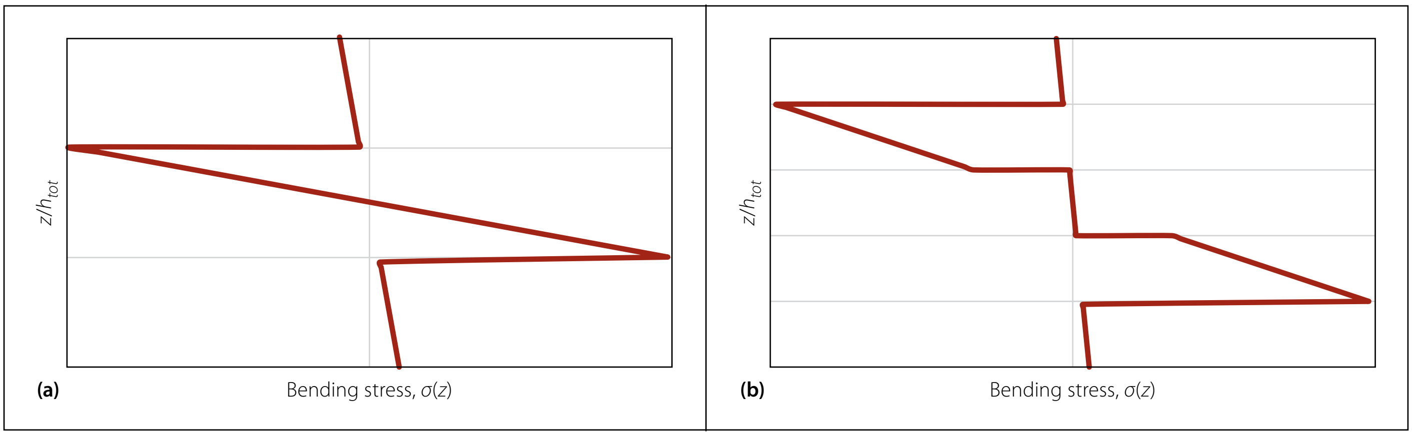

Figure 5 Minor direction bending stress distributions in a) three-layer and b) five-layer CLT cross sections

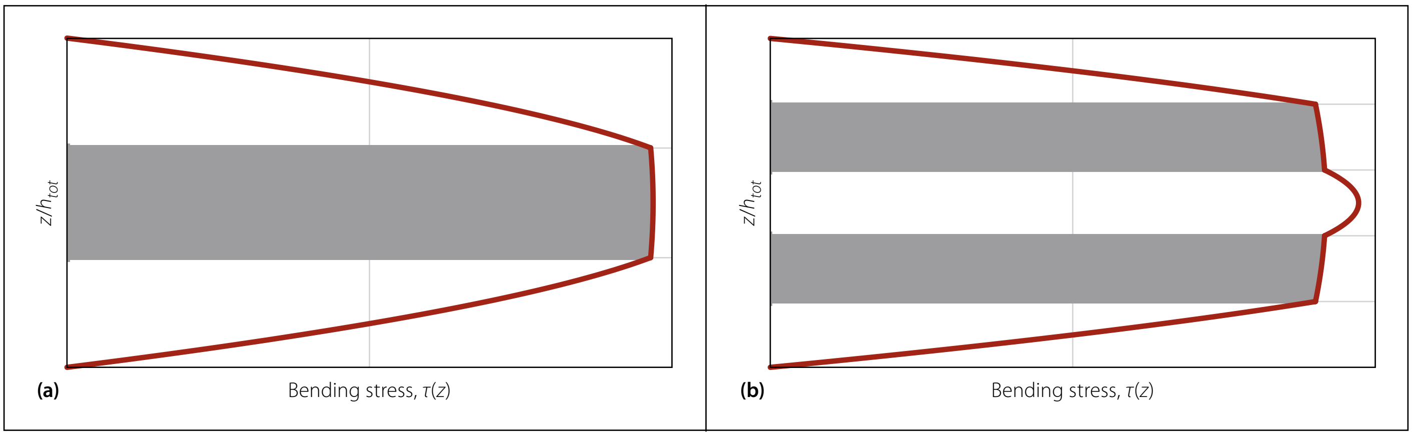

Figure 6 Major direction shear stress distributions in a) three-layer and b) five-layer CLT cross sections (rolling shear stresses shaded)

and established factors provided for sawn timber in South Africa in SANS 10163-1 (2003) could be reasonably extended to CLT design, as is the case with plywood design.

Naturally, CLT has a more complex cross section than sawn timber, making regular moment resistance equations unsuitable for designing CLT members. Therefore, it is proposed that potential design standards incorporate analytical methods, allowing for more CLT-specific resistance equations. Due to its relative accuracy regarding apparent bending stiffness, as well as its relatively intuitive and general stress equations, Timoshenko beam theory is proposed as a basis for potential CLT design equations. While the shear analogy method has also proven to be comparatively accurate, the stress equations proposed in the shear analogy method are relatively complex, as well as span dependent. The bending stress within the cross section using Timoshenko beam theory is given by Equation 16 and visualised for major and minor direction bending in Figure 4 and Figure 5, respectively, for symmetrical three- and five-layer CLT layups, assuming layers of equal thickness and stiffness. The perpendicular stiffness was assumed as 30 times less than the parallel stiffness, an assumption made in ANSI/APA PRG 320 (2017).

$$\sigma(z) = \frac{M \cdot E_i}{E_{eff}} \cdot (\bar{y} - z) \qquad (16)$$

Where: z is the position within the cross-section (mm), $\sigma(z)$ is the bending stress at z (MPa), and $\bar{y}$ is the centroid of the cross section (mm).

The shear stress within the cross section, shown in Equation 17, includes a term for the product of the elastic modulus and the static moment at z. This term is given by

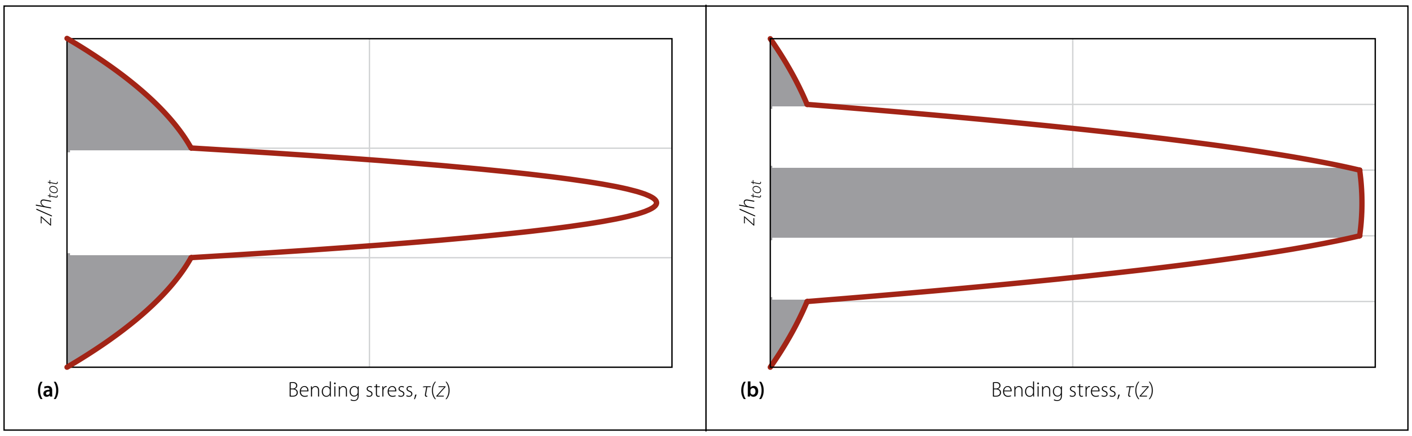

Figure 7 Minor direction shear stress distributions in a) three-layer and b) five-layer CLT cross sections (rolling shear stresses shaded)

Equation 18 and is critical to distinguishing the maximum planar and rolling shear stresses. Given the disparity between the planar and rolling shear strength of timber outlined in SANS 10163-1 (2003), both require consideration in sensible CLT design. The shear stress within the cross section is visualised for major and minor direction bending in Figure 6 and Figure 7, respectively, for symmetrical three- and five-layer CLT layups, with shaded regions representing rolling shear stresses. Equation 19 defines the distance from the bottom of layer i to the bottom of the cross-section, keeping in mind the layer numbering scheme presented in Figure 1.

$$\tau(z) = \frac{V \cdot EQ(z)}{EI_{eff} \cdot b} \quad (17)$$

$$EQ(z) = \sum_{i=1}^{j-1} E_i \cdot A_i \cdot y_i + E_i \cdot b\,(z - d_j) \cdot \left(\bar{y} - d_j - \frac{z - d_j}{2}\right) \quad (18)$$

$$d_i = h_i + h_2 + h_3 \ldots + h_{i-1} \quad (19)$$

Where: $\tau(z)$ is the shear stress at z (MPa), V is the applied shear force (N), and d_i is the distance from the bottom of layer i to the bottom of the cross section (mm).

The bending resistance equation for sawn timber in SANS 10163-1 (2003) includes the section modulus. With CLT layups, especially asymmetric and hybrid layups, the section modulus is not easily determined. A CLT-specific equation would ideally include a layup-specific effective bending stiffness, along with the elastic modulus for the outer-most layers oriented in the direction of the span. This would typically be either E_1 or E_n and the proposed equation for bending moment resistance for CLT orientated in the major direction may appear as shown in Equation 20.

$$M_{r,M} = min \begin{Bmatrix} \dfrac{f_{b,1}}{\bar{y}} \cdot \dfrac{EI_{eff,M}}{E_1} \cdot \dfrac{\phi}{\gamma_{m1} \cdot \gamma_{m2} \cdot \gamma_{m3} \cdot \gamma_{m5}} \\ \dfrac{f_{b,n}}{(h_{tot} - \bar{y})} \cdot \dfrac{EI_{eff,M}}{E_n} \cdot \dfrac{\phi}{\gamma_{m1} \cdot \gamma_{m2} \cdot \gamma_{m3} \cdot \gamma_{m5}} \end{Bmatrix} \quad (20)$$

Where: $M_{r,M}$ is the ultimate major direction bending moment resistance (Nmm), $f_{b,i}$ is the characteristic bending strength of layer i (i = 1, n in MPa) and $EI_{eff,M}$ is the effective major direction bending stiffness (Nmm^2).

For minor direction bending calculations, it is suggested that the resistance from the outer layers is neglected. Therefore, the ultimate minor direction bending moment resistance can be calculated using Equation 21.

$$M_{r,M} = min \begin{Bmatrix} \dfrac{f_{b,2}}{(\bar{y} - h_1)} \cdot \dfrac{EI_{eff,m}}{E_2} \cdot \dfrac{\phi}{\gamma_{m1} \cdot \gamma_{m2} \cdot \gamma_{m3} \cdot \gamma_{m5}} \\ \dfrac{f_{b,n-1}}{(h_{tot} - \bar{y} - h_1)} \cdot \dfrac{EI_{eff,m}}{E_{n-1}} \cdot \dfrac{\phi}{\gamma_{m1} \cdot \gamma_{m2} \cdot \gamma_{m3} \cdot \gamma_{m5}} \end{Bmatrix} \quad (21)$$

Where: $M_{r,m}$ is the ultimate minor direction bending moment resistance (Nmm), and $EI_{eff,m}$ is the effective minor direction bending stiffness (Nmm^2).

Under bending, regular sawn timber sections will experience both compressive and tensile stresses within the cross-section. However, in CLT, as shown in Figure 4 and Figure 5, individual layers may experience purely compressive stresses or purely tensile stresses. Since, according to SANS 10163-1 (2003) and SANS 1707-1, the tensile resistance for all South African timber grades is taken as less than the bending resistance, it may be more appropriate for engineers to consider the tensile resistance of the lamellae rather than the bending resistance as shown in Equation 20 and Equation 21. However, this consideration requires further research focusing on the bending resistance of CLT.

The rolling shear factor in prEN 1995-1-1 (2023), $k_{r,pu}$, with a value of 1.6, may appear to be unconservative. However, Ehrhart *et al* (2015) performed rolling shear tests on various European timber species and recommended a characteristic rolling shear strength of 1.4 MPa for spruce (the weakest species tested), while prEN 1995-1-1 (2023) recommends a characteristic rolling shear strength for CL24 class CLT as 0.7 MPa. SANS 10163-1 (2003) stipulates that the rolling shear strength be taken as 25% of the planar shear strength, which translates to 0.4 MPa for grade S5 structural pine. From the 40 shear tests conducted by Jacobs (2023) on three-layer South African pine CLT, the lowest individual rolling shear strength obtained was 1.69 MPa.

However, estimating shear stress with Timoshenko beam theory is difficult due to the layup-dependent nature of the analysis equations. These equations yield results as stresses, in comparison to the philosophy of SANS 10163-1 (2003) which calculates resistance values in terms of forces and moments. Furthermore, the equation for shear resistance in SANS 10163-1 (2003) includes a term for the shear area of the section, which is taken as the product of the section width and height in rectangular sections. The shear stress is not constant across the cross section of a CLT layup. The rolling shear strength of the transverse layer is highly likely to govern over the planar shear strength in the longitudinal layers in most design cases. Nevertheless, both should be considered and the formula for the shear resistance may appear as shown in Equation 22.

$$V_r = min \begin{Bmatrix} \dfrac{f_v \cdot EI_{eff} \cdot b}{EQ_{cr,v}} \\ \dfrac{f_r \cdot EI_{eff} \cdot b}{EQ_{cr,r}} \end{Bmatrix} \quad (22)$$

Where: V_r is the ultimate shear resistance (N), f_v is the characteristic planar shear strength (MPa), f_r is the characteristic rolling shear strength (MPa), and EQ_{cr} is the critical product of the elastic moment and the first moment of area (Nmm).

The critical product of the elastic moment and the first moment of area may differ between planar and rolling shear stresses. For a symmetrical three-layer configuration under major-direction loading (Figure 7a), the maximum shear stress which occurs at the centre of the middle layer is a rolling shear stress. From Figure 7b for a five-layer CLT layup, the maximum planar shear stress (which is also the maximum overall shear stress) occurs at the centre of the middle layer, while the maximum rolling shear stress occurs at the interface between the middle layer (layer 3) and its adjacent transverse layers (layers 2 and 4). This results in critical product of the elastic moment and the first moment of area terms shown in Equation 23 and Equation 24 for the critical planar and rolling shear stresses, respectively (adapted from Karacabeyli & Gagnon 2019).

$$EQ_{cr,v} = E_1 \cdot A_1 \cdot y_1 + E_2 \cdot A_2 \cdot y_2 + \frac{E_3 \cdot A_3 \cdot h_3}{8} \quad (23)$$

$$EQ_{cr,r} = E_1 \cdot A_1 \cdot y_1 + E_2 \cdot A_2 \cdot y_2 \quad (24)$$

MATERIAL RESISTANCE FACTOR

This section serves, in part, as a preliminary desktop investigation towards a more appropriate resistance factor for CLT in South Africa. In SANS 10163-1 (2003), a material resistance factor, ϕ, of 0.68 is recommended for timber. In prEN 1995-1-1 (2023), γ_M is taken as 1.25 for CLT which is equivalent to a material resistance factor, ϕ, of 0.8, as shown in Equation 25. These factors are considered to account for material variability in structural design and are determined considering variances observed in studies investigating large sample sizes. One of the benefits of CLT (and EWPs in general) is a reduction in material property variability, on account of its dispersing properties (Schickhofer *et al* 2016; Kurzinski *et al* 2022). However, appropriate large sample size testing is more costly for CLT than for sawn timber.

$$\frac{1}{\gamma_M} = \phi \quad (25)$$

Where: γ_M and ϕ are both partial factors for material resistance.

EN 1995-1-1 (2008) proposes a material resistance factor, γ_M, of 1.30 for sawn timber, a value that has remained unchanged in prEN 1995-1-1 (2023), representing a value 4% higher than the value of 1.25 proposed for CLT. Applying a similar increase to the South African resistance factor, ϕ, of 0.68 for sawn timber proposed in SANS 10163-1 (2003) yields a hypothetical value of 0.71 for CLT.

Pagel (2019) explored and proposed material resistance factors for young, South African sawn and laminated eucalyptus timber. He outlined the calculation procedures to determine material resistance factors based on experimental result variability. Adopting this statistical model using the variance from published CLT results might propose a more refined solution in determining an appropriate partial factor for material resistance for CLT in South Africa.

Statistical model

The formula for the material resistance factor, γ_M, is defined by Holický (2009) and is shown in Equation 26:

$$\gamma_M = \gamma_m \cdot \gamma_{Rd} \quad (26)$$

Where: γ_m is the material property factor, and γ_{Rd} is the model uncertainty factor.

The inverse of this model was considered by Pagel (2019) to obtain the material resistance factor of SANS 10163-1 (2003), as shown in Equation 27:

$$\phi = \phi_m \cdot \phi_{Rd} \quad (27)$$

Where: ϕ_m is the material property factor, and ϕ_{Rd} is the model uncertainty factor.

The equations for the material property factor and the model uncertainty factor, as given by Pagel (2019), are shown in Equation 28 and Equation 29, respectively. Equation 28 is simplified for when the 5th percentile value is used as the characteristic value, as is typical for ultimate limit state design. The first order reliability method (FORM) sensitivity factor is taken as 0.8, provided the assumption shown in Equation 30 holds, as stated in EN 1990 (2002). SANS 10160-1 (2019) requires a minimum reliability factor of 3 for reliability class 2 structures (which includes residential, office and public buildings).

The values for model uncertainty variables are taken from the JCSS Probabilistic Model Code (2006). The mean of the model uncertainty variable is taken as 1. Two options are given regarding the standard deviation of the model uncertainty variable: 0.1 with load duration effects, and between 0.05 and 0.1 without load duration effects. Since the coefficient of variation is taken from test results on specimens containing new, unused material, the effect of load duration is neglected. According to the JCSS Probabilistic Model Code (2006), the model uncertainty depends on the deviation between actual conditions and standard test conditions. Assuming the tests conducted by Jacobs (2023) were performed in laboratory conditions, the standard deviation, and, subsequently, the coefficient of variation of the model uncertainty variable is taken as 0.05.

$$\phi_m = e^{-(\alpha_R \cdot \beta - 1.645) \cdot CV_m} \quad (28)$$

$$\phi_{Rd} = (\mu_{\theta R} \cdot e^{\alpha_R \cdot \beta \cdot CV_{\theta R}})^{-1} \quad (29)$$

$$0.16 < \frac{\sigma_E}{\sigma_R} < 7.6 \quad (30)$$

Where: α_R is the FORM sensitivity factor (α_R = 0.8), β is the target reliability factor (β = 3), CV_m is the coefficient of variation of the material resistance, $\mu_{\theta R}$ is the mean of the model uncertainty variable ($\mu_{\theta R}$ = 1), $CV_{\theta R}$ is the coefficient of variation of the model uncertainty variable, σ_E is the standard deviation the action effect, and σ_R is the standard deviation of material resistance.

Results-based factor

Jacobs (2023) investigated the major and minor direction out-of-plane performance of three-layer CLT composed of South African pine lamellae. He investigated 66 mm and 138 mm layups. Pine accounts for most structural timber in South Africa, with around 75% of pine grown for sawlog

Table 2 Material resistance factors calculated using values obtained by Jacobs (2023)

Layup	Direction	Test	V_m	φ_{Rd}	φ_m	φ
66 mm	Major	Bending	15.02%	0.89	0.89	0.79
		Shear	9.63%		0.93	0.82
	Minor	Bending	13.33%		0.90	0.80
		Shear	13.97%		0.90	0.80
138 mm	Major	Bending	21.08%		0.85	0.76
		Shear	4.96%		0.96	0.85
	Minor	Bending	20.68%		0.86	0.76
		Shear	25.32%		0.83	0.73
Total average						0.79

production (DFFE 2018). Therefore, the material resistance factor calculated using the results obtained by Jacobs (2023) might be considered as an indication of CLT's material variability.

To this end, the material resistance factor for each test configuration performed by Jacobs (2023) is calculated here, with results summarised in Table 2. For each test, the coefficient of variation is used to calculate the material property factor. It should be noted that these coefficient of variation values are taken from the maximum applied force for each test (since constant dimensions were used in the strength calculations, this will not affect the coefficient of variation values for bending strength). Each test comprised 10 samples. Because of the assumptions made with respect to the mean and standard deviation of the model uncertainty variable, the model uncertainty factor is constant across all calculations.

Using the coefficients of variation from Jacobs (2023), the resulting material resistance factor is 0.79, higher than the 0.68 value in SANS 10163-1 (2003), and only slightly lower than the effective value of 0.8 defined for CLT in prEN 1995-1-1 (2023). The most variable results were present in the 138 mm minor shear tests, with a coefficient of variation of 25.32%, resulting in a resistance factor of 0.73, still higher than 0.68.

Pagel (2019) recommended a resulting material resistance factor of 0.77 for young, finger-jointed eucalyptus, suggesting a higher homogeneity of material properties (namely bending strength and stiffness) than pine. Therefore, a higher material resistance factor, ϕ, may be more suitable for eucalyptus CLT or hybrid layups with eucalyptus and pine. However, a value based on pine-only layups might be appropriate until experimental validations shows otherwise. This value should also consider a larger sample size than what has been considered to date.

CONCLUSIONS

This study aimed to recommend procedures for the preliminary design of structural CLT in South Africa using established local timber design principles. Based on the findings of this study, the following conclusions can be drawn:

- Timoshenko beam theory and the shear analogy method appear to be the most accurate analytical method used in CLT property estimation. However, the relative simplicity of Timoshenko beam theory led the authors to recommend its integration in future CLT design codes developed in South Africa.
- The partial factors defined for CLT in prEN 1995-1-1 (2023) are generally the same as those used for sawn timber. Such an approach would lend well to SANS 10163-1 (2003), simplifying CLT design with proven and established partial factors, similar to the approach taken with respect to plywood design. Resistance equations would, however, require modifications to account for CLT's more complex cross-sectional layup compared to sawn timber.
- Adopting the proposals made in prEN 1995-1-1 (2023), a material resistance factor, ϕ, of 0.71 could be applied to CLT in South Africa, compared to the value of 0.68 currently proposed for sawn timber in SANS 10163-1 (2003). However, using the methods used by Pagel (2019), coupled with the coefficients of variation obtained by Jacobs (2023) for South Africa pine-only CLT, yielded an average estimated resistance factor of 0.79.

CLT is still a relatively new and unexplored field of research in South Africa. The following focus areas are therefore recommended for future investigation:

- The current partial material factors defined in SANS 10163-1 (2003) appear to be mainly suited to sawn timber design. Future consideration should be targeted towards proposing CLT-specific provisions for these factors.
- More extensive research is recommended into a CLT partial material resistance factor before a factor for CLT in South Africa is adopted in reasonable confidence. Furthermore, any differences in the mean strength values of CLT compared to that of sawn timber should be investigated.
- The rolling shear properties of South African timber should receive thorough investigation. Given the results obtained in the literature for similar species to those grown in South Africa, and the factors applied to rolling shear strength in prEN 1995-1-1 (2023), currently defined rolling shear strengths may be overly conservative and complicate CLT design procedures.
- The relation between the bending resistance of CLT and the sawn timber lamellae of which it is composed should be investigated to inform safer and more sensible design procedures.

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