Defining perpendicular to grain compression stress: A comparison of methods and recommendations for ASTM D143

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Abstract: The reliable characterization of structural properties is essential for safe and efficient structural design. This paper focuses on the behavior of lumber under compression load perpendicular to the grain. Emphasis is made on defining a standardized method for determining yield stress for tests performed in accordance with ASTM D143, primarily motivated by the need for well-defined material properties for finite element constitutive models. This research compared the existing standard test methods published by the European Committee for Standardization (CEN), International Standards Organization (ISO), and ASTM International by analyzing a series of tests performed in accordance with ASTM D143. A literature review showed that there is no dominant method for calculating strength of wood in compression perpendicular to the grain and that analysis methods are not always clearly described or aligned with the standard used for testing. Experimental results indicated that the various calculation methodologies produce significantly different strength properties; as such, a standardized calculation methodology should be implemented for use with ASTM D143 testing procedures. It is recommended that the methods for determining yield stress specified in EN 12512 should be applied to experimental data resulting from specimens tested in accordance with ASTM D143.

Keywords: Clear wood compression strength; Perpendicular to grain; Yield stress; ASTM D143

Introduction

Compression perpendicular to grain stress describes a fundamental mechanical behavior that is important for the analysis and design of bearings and connections for timber buildings. There are several international standards for characterizing perpendicular to grain compressive stress. However, these standards vary in specimen dimensions, load configuration, and definition of compressive stress. This is because some standards aim to characterize basic material properties, while others reflect typical uses (Leijten et al. 2010). The lack of unified approach to determining the standard compression perpendicular to grain strength makes it difficult to determine consistent strength values.

Computational modeling is rapidly advancing in the field of wood mechanics. There are currently several finite element software programs which offer different material models to simulate the elastoplastic and orthotropic behavior of wood (Crespo et al. 2020). However, the predictive capability of such models is fundamentally constrained by the accuracy of the input material properties. Reliable characterization of wood under fundamental loading scenarios is therefore critical for deriving the parameters required in finite element modeling (FEM).

There are several material models for wood that can be applied in FEM; however, most nonlinear constitutive models require, at a minimum, the specification of an elastic modulus and yield stress. For compression perpendicular to grain, the yield stress is different from the design value published in the National Design Specification for Wood Construction (NDS) which is a deflection serviceability limit (American Wood Council 2024). As such, determining the most appropriate stress value for use in FEM analyses is required.

The stress that distinguishes between elastic and plastic behavior of a material is sometimes called the yield point, proportional limit, elastic limit, or yield stress. Although each of these terms are used to describe that point at which the material transitions from elastic to plastic behavior, they often are understood with somewhat different interpretations (Christensen 2008). The proportional limit is the stress at which the stress-strain relationship becomes nonlinear. Defining the proportional limit can be challenging since the transition from linear to nonlinear deformation is gradual. The yield stress is typically

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an engineering definition specified by a standard approach. In steel products, for example, the yield stress is defined by an offset method, where the yield stress is defined by drawing a line, offset by 0.2% strain, parallel to the elastic portion of the stress-strain curve (Instron 2023). The point where the line intersects the stress-strain curve is defined as the yield stress (ASTM International 2024). No existing ASTM standards specify a calculation method for defining the yield stress of wood in compression perpendicular to the grain.

The objective of this work is to provide a recommendation for defining compression perpendicular to grain yield stress for tests performed in accordance with ASTM D143, Test Methods for Small Clear Specimens of Timber (ASTM International 2022a), based primarily on a literature review and experimental program.

To this end, a literature review of North American and European standards for characterizing compression perpendicular to grain properties was performed to identify the existing methods for defining compression perpendicular to grain stress. A review of the academic research literature was also performed to evaluate current practices and how the standards are applied in practice.

Spruce-pine-fir (SPF) specimens were then tested in accordance with ASTM D143 (ASTM International 2022a). Several standard methods for defining compression perpendicular to grain stress were then applied to compare the analytical methods. Statistical results were computed and the parameters required for computational modeling of compression perpendicular to grain behavior are presented. Recommendations for automating the calculation of compression yield stress with tests performed in accordance with ASTM D143 are provided.

Background

Organizations such as the American Society of Testing and Materials (ASTM), the International Organization for Standardization (ISO), and the European Committee for Standardization (CEN) maintain standard procedures for defining wood properties. There are currently two general philosophies for mechanical property testing: tests can be performed with small, clear, wood samples or structural scale specimens. Clear wood properties are valuable for determining material properties without the effects of defects, whereas structural scale specimens are commonly used for defining structural design values (Arriaga et al. 2023).

ASTM D143

In North America, ASTM International Committee D07 on Wood has jurisdiction over several standards which provide fundamental test methods for characterizing wood properties and establishing structural grades and design values. The scope of each standard is summarized in Table 1. Historically, reference design values for visually graded dimension lumber were developed from small clear specimens of timber. Experimental testing was performed in accordance with ASTM D143 (ASTM International 2022a), and allowable stress and modulus of elasticity values were determined using the procedures of ASTM D245, Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber (ASTM International 2022b), and ASTM D2555, Standard Practice for Establishing Clear Wood Strength Values (ASTM International 2006). With the introduction of mechanical testing equipment capable of rapidly testing full-size structural members, it is now standard practice for allowable stress and modulus of elasticity values to be derived from tests of full-size structural members conducted in accordance with ASTM D198, Test Methods of Static Tests of Lumber in Structural Sizes (ASTM International 2022c). The transition from clear wood to structural scale specimens was implemented in the North American In-Grade Test Program.

While many of the reference design values are obtained through structural scale specimens in accordance with the methods of ASTM D198 (ASTM International 2022c) and ASTM D1990, Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens (ASTM International 2025a), allowable stress values for compression perpendicular to grain continue to be calculated from small, clear wood, specimens using the procedures of ASTM D143 (ASTM International 2022a), ASTM D245 (ASTM International 2022b), and ASTM D2555 (ASTM International 2006).

ASTM D143 specifies that a 50 mm by 50 mm by 150 mm (2 in. by 2 in. by 6 in.) specimen be loaded through a 50 mm (2 in.) wide metal bearing plate placed over the central third of the specimen surface. The metal bearing plate is loaded in compression through a spherical bearing, with the specimen placed so that load is applied through the bearing plate to a radial surface, at a rate of deflection of 0.305 mm (0.012 in.) per minute until a 2.5 mm (0.1 in.) compression deformation is achieved. Compression deformation is measured between the loading surfaces (ASTM International 2022a). This testing procedure was originally developed to represent a 50 mm (2 in.) wide wood joist resting on a wall or foundation (Pellicane et al. 1994).

ASTM D245 states that the stress at the proportional limit in compression perpendicular to grain and stress in compression

Table 1. Summary of ASTM standards for wood property characterization.

ASTM Standard	Summary of standard scope
ASTM D143 – Standard Test Methods for Small Clear Specimens of Timber (ASTM International 2022a)	Provides standard test methodology for clear wood, small-scale mechanical tests.
ASTM D198 – Standard Test Methods of Static Tests of Lumber in Structural Sizes (ASTM International 2022c)	Provides standard test methodology for structural-scale mechanical tests.
ASTM D245 – Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber (ASTM International 2022b)	Provides provisions for assigning reference design values for some species and grades of visually graded dimension lumber.
ASTM D1990 – Standard Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens (ASTM International 2025a)	Evolved from ASTM D245; provides provisions for assigning reference design values for most species and grades of visually graded dimension lumber.
ASTM D2555 – Standard Practice for Establishing Clear Wood Strength Values (ASTM International 2006)	Referenced in ASTM D245; used to adjust strength properties of clear wood specimens to obtain reference design values applicable to normal service conditions.

perpendicular to grain at 1 mm (0.04 in.) deformation shall be obtained from ASTM D2555 (ASTM International 2006; ASTM International 2022b). The 1 mm deformation stress represents a serviceability displacement limit state, rather than a strength limit state.

In the 1977 and earlier editions of the NDS, reference design values for compression perpendicular to grain were based on proportional limit and adjusted for load duration (American Wood Council 2024). This approach was revised when ASTM D245 reclassified compression perpendicular to grain as a serviceability limit state, reframing the property as a measure of bearing deformation rather than a stress criterion (ASTM International 2022b). Since 1982, reference design values for compression perpendicular to grain have been established at a uniform deformation limit of 1 mm under a steel plate on wood bearing condition and are no longer subject to load duration adjustment (American Wood Council 2024).

Compression perpendicular to grain behavior of softwood lumber exhibits a linear-elastic initial response before yielding and experiencing an approximately linear response with a reduced modulus with considerable plastic deformation. Compressive loading perpendicular to the grain can lead to a high degree of densification, particularly in the radial direction (Arriaga et al. 2023). Identifying the proportional limit of the linear-elastic region can be difficult because the transition from linear to nonlinear is gradual. ASTM D2555 does not specify a method for identifying the proportional limit (ASTM International 2006).

Neither ASTM D245 nor ASTM D2555 provide provisions for determining compression yield stress (ASTM International 2006; ASTM International 2022b). As such, it is assumed that yield stress should be defined visually on the stress-strain curve as the end of the linear-elastic regime.

ISO 13061-5

The International Organization for Standardization (ISO) is an international federation of national standards bodies. ISO Technical Committee 218 *Timber* has jurisdiction over ISO 13061-5, *Physical and mechanical properties of wood—Test methods for small clear wood specimens Part 5: Determination of strength in compression perpendicular to grain* (International Organization for Standardization 2020). This standard has been utilized in many countries around the world including Australia, New Zealand, and some Asian countries. It is also assumed in many European countries since the European Committee for Standardization (CEN) does not currently provide guidance for testing small clear wood specimens (Arriaga et al. 2023).

ISO 13061-5 provides both test procedures and analysis methods for compression perpendicular to grain properties. The clear wood specimen height, H, should be 20 to 50 mm (0.8 to 2 in.), length, L, should be 1.5 to 3 times the height, and the width, W, should be greater than or equal to half of the height. Loading should be applied radially, tangentially, or at an angle of 45 to the growth rings, at a constant rate such that yield is reached within 1 to 5 min (60 to 300 s), and specimens are loaded until 5% deformation. With regards to sensing, it states, "When using a testing machine without an accurate recording device, a displacement measuring device shall be used to determine the deformation of the height" (International Organization for Standardization 2020). ISO 13061-5 specifies that the proportional limit in compression perpendicular to the grain should be defined as the ordinate of the point where the tangent of the angle formed by the load axis with the tangent to the load-deformation curve is 50% greater than its value in the linear portion of the diagram. The proportional limit stress is then the load at the proportional limit divided by the bearing area (International Organization for Standardization 2020).

EN 408

The European standard, EN 408, *Timber structures—Structural timber and glued laminated timber—Determination of some physical and mechanical properties*, does not limit samples to clear wood; instead, it applies broadly to solid wood, glued laminated timber, and other wood-based products (British Standards Institution 2012). For compression perpendicular to grain, EN 408 provides both testing and calculation guidelines for the compression stress and modulus of elasticity. For testing structural timber, EN 408 calls for a 45 mm by 90 mm by 70 mm (1.8 in. by 3.5 in. by 2.8 in.) specimen to be loaded over the entire length of the sample through spherically seated loading heads; the load rate should be determined so the maximum load is reached within 5 ± 2 min (300 ± 120 s). EN 408 also specifies that displacement should be measured by two extensometers centered on the specimen on opposite sides with a gauge length approximately equaling 60% of the height of the sample (British Standards Institution 2012).

The compression stress is calculated using an iterative method in which the maximum compressive force, $F_{C,90,max,est}$, is estimated visually, and the modulus of elasticity, *E,* is calculated by

$$E = \frac{(F_{40} - F_{10})h_0}{(w_{40} - w_{10})bl} \quad [1]$$

where F_{40} and F_{10} correspond to the 40% and 10% of the estimated maximum compressive force, $F_{C,90,max,est}$, and w_{40} and w_{10} are the deformations corresponding to F_{40} and F_{10}.The gauge length, specimen width, and specimen length are h_0, b, and l, respectively. A line is then drawn with a slope of E and originating at a force of 0 and deformation equal to 1% of h_0. If the point of intersection of this line and the experimental data is within 5% of $F_{C,90,max,est}$, then that load may be used to determine the compressive stress by:

$$f = \frac{F_{c,90,max}}{bl}. \quad [2]$$

Otherwise, the procedure is repeated until a value of $F_{C,90,max}$ within the 5% tolerance limit is obtained. The subscript *max* utilized in $F_{C,90,max}$ and $F_{C,90,max,est}$ is not referring to the maximum load reached during a test but rather the load at the maximum compressive stress, as defined by EN 408. Notably, EN 408 defines *compression* stress in perpendicular to grain and does not define a *yield* stress (British Standards Institution 2012).

EN 12512

The European standard, EN 12512, *Timber Structures – Test Methods – Cyclic testing of joints made with mechanical fasteners*, is not intended for defining fundamental material properties of wood; instead, it specifies a test method for determining "the ductility, impairment of strength, and energy dissipation properties of joints made with mechanical fasteners under cyclic loading" (British Standards Institution 2005). Although the specified test methods do not apply to this study, the standard provides a well-defined approach to defining yield load that could be applied to defining the compression perpendicular to grain yield stress. In Method A of EN 12512 (referred to hereafter as "12512a"), which is applied when the load-slip curve presents two well-defined linear sections, the yield load is determined by the intersection between these two lines. This can be modified to be applied to a stress-strain curve. EN 12512 also provides Method B (referred to hereafter as "12512b") for defining the yield load when the yield-slip curve does not have two well-defined linear sections. In this method, the yield values are determined by the intersection of two lines. The first line is drawn through the point on the load-slip curve corresponding to $0.1F_{max}$ and $0.4F_{max}$. The second line is the tangent having an inclination of 1/6 of the first line (British Standards Institution 2005).

Comparison of Test Procedures

The three primary test methodologies considered in this paper for compression perpendicular to grain are ASTM D143 (ASTM International 2022a), EN 408, and ISO 13061-5 (British Standards Institution 2012; International Organization for Standardization 2020). Both ASTM D143 and ISO 13061-5 pertain to small, clear wood specimens, while EN 408 permits larger scale specimens. In ASTM D143, the load is transmitted through a metallic loading block that does not cover the entire area of the specimen, leading to higher compression perpendicular to grain values than in cases in which the load is applied over the full area of the specimen (Kunesh 1968; Bodig 1969; Pellicane et al. 1994, as cited in Basta et al. 2011). In contrast, both EN 408 and ISO 13061-5 transfer compression load through the full area of the cross-section. The ASTM loading procedure is intended to reflect typical loading conditions, such as a beam fully supported on a bearing wall or foundation, and loaded by a square stud (Bodig and Jayne 1982, as cited by Leijten et al. 2012). The EN 408 method aims to define physical material properties, rather than properties related to typical applications. A summary of the test methodologies is provided in Table 2. While EN 12512 is considered in this study as a calculation method, the specific testing procedure

Table 2. Comparison of test methodologies.

Standard	Specimen dimensions (mm)	Bearing plate location	Displacement measurement	Test rate
ASTM D143 (ASTM International 2022a)	50 × 50 × 150	Local center through radial surface	Measured across entire length of specimen	0.305 mm/min up to 2.5 mm displacement
EN 408 (British Standards Institution 2012)	45 × 90 × 70	Full area	Two extensometers on opposite sides of sample; Gauge length of approx. 0.6h and shall be located centrally in the test piece height	Compressive stress reached in 5 min ± 2 min
ISO 13061-5 (International Organization for Standardization 2020)	H = 20 to 50; L = 1.5H to 3H; W 0.5H	Full area	Not specified	Proportional limit is reached in 1–5 min

is not discussed here, as it is not intended for material property characterization (British Standards Institution 2005).

Leijten et al. (2012) provide an assessment and comparison of testing procedures for determining the compressive stress of wood in compression perpendicular to the grain and demonstrate a model for making testing results compatible when using the various procedures (Leijten et al. 2012). However, they consider ASTM D143 to define the compressive stress of wood in compression perpendicular to the grain at 1 mm which represents the serviceability limit specified by ASTM D245 (ASTM International 2022a; ASTM International 2022b). The study presented in this manuscript builds on the work of Leijten et al. (2012) by suggesting standardized analysis methodology for calculating yield stress, rather than a serviceability limit, for tests performed in accordance with ASTM D143.

Methodology

Literature review

A literature review was conducted using the Web of Science search engine to identify publications that performed compression perpendicular to grain tests and defined the compressive stress of wood (Web of Science Master Journal List - WoS MJL by Clarivate). The key terms "compression" AND ("perpendicular-to" OR "perpendicular to") AND ("wood" OR "lumber" OR "clear wood") OR "strength" were applied to titles, abstracts, and keywords for papers. Results were filtered to include only papers published between 2010 and 2025 and limited to Web of Science Categories relevant to this research. This yielded 180 papers; of these, 169 were obtained in English through public or institutional access and then reviewed to determine relevance with respect to this investigation.

Experimental testing

Experimental testing was performed in accordance with ASTM D143: Test Methods for Small Clear Specimens of Timber. ASTM D143 is the standard procedure used in North America for determining wood compression properties but does not provide specific guidance for defining compression perpendicular to grain yield stress (ASTM International 2022a).

Materials

Twenty-one 3048 mm (10 ft.)-long nominal 2×6 SPF boards with a 2100fb 1.8E rating were sourced from Spokane, WA. Samples taken from four different boards were sent to external labs for species identification. The results indicated that the samples were in the yellow pine, or western hard pine, group. Two of the samples were identified as radiata pine (*Pinus radiata*) and two of the samples were identified as likely lodgepole pine (*Pinus contorta*).

ASTM D143 specifies compression perpendicular to grain samples to be rectangular prisms with dimensions of 50 mm by 50 mm by 150 mm (2 in. by 2 in. by 6 in.). Due to constraints in the cross-sectional dimensions of the source lumber, samples were manufactured to 45 mm by 45 mm by 150 mm (1.75 in. by 1.75 in. by 6 in.) (ASTM International 2022a) (Figure 1A). Samples of required dimensions could not be obtained from 3 out of the 21 boards due to the presence of defects in these boards. As such, 18 specimens were manufactured. After manufacturing, samples were moisture conditioned in a steady-state conditioning chamber set to 20C and 65% relative humidity to achieve 12% ± 3% moisture content.

The specimens were weighed immediately prior to testing. After testing, the specimens were placed in an oven at 105°C for 24 h. Specimens were then weighed and placed back into the oven until the change in oven-dry weight was less than 1% over 24 h. The moisture content was determined by ASTM D4442, Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials (ASTM International 2025b): MC (%) = 100 ($W_W - W_{OD}$) / W_{OD}, where W_{OD} is the oven-dry weight and W_W is the pre-test weight.

Testing procedure

Specimen depth, width, and length were measured at three different points on each sample. The average values were used

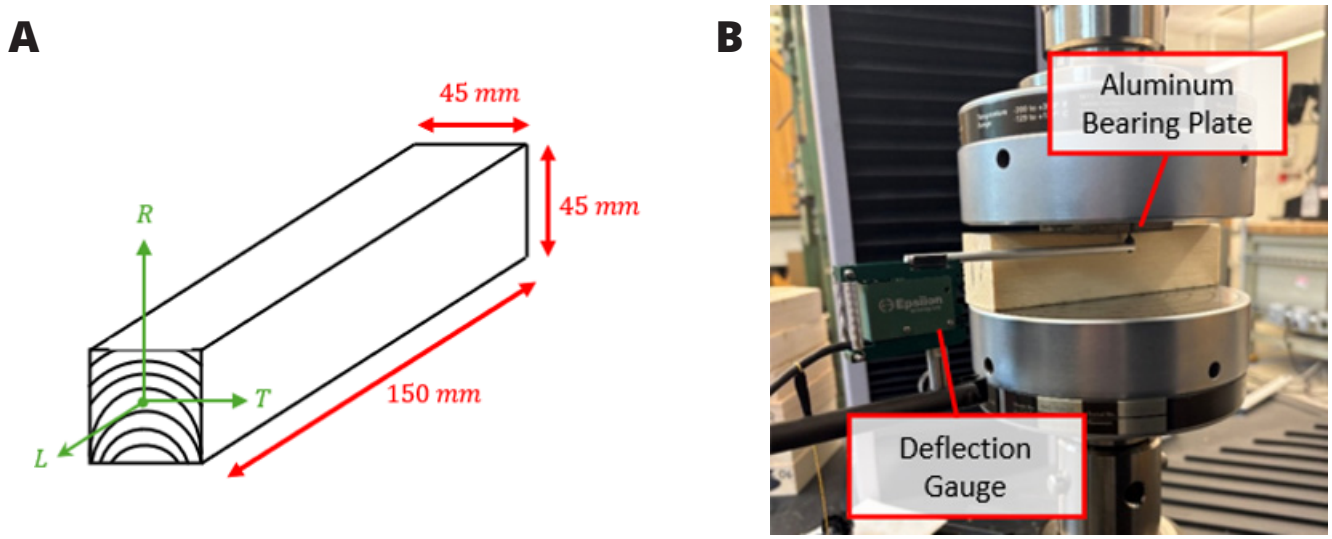


Figure 1. Experimental test assembly for compression perpendicular to grain.(A) Specimen geometry; (B) Test set up.

in stress and strain calculations. Specimens were tested in a 66-kip Electromechanical Universal Testing Machine (MTS Systems, MTS Criterion C45.305). Compression was loaded through rigid platens to the radial surface. A 50 mm (2 in.) wide aluminum bearing plate was placed between the platen and upper surface of the specimen at equal distances from the end of the specimen. In accordance with ASTM D143, deflection was measured between the loading surfaces; a deflection gauge (Epsilon Technology Corp., 3540-025T-ST; measuring range: 6.4 mm (0.25 in.); accuracy: ASTM E2309 Class A, ISO 9513 Class 1) was placed beneath the aluminum plate. Compression load was applied at a constant crosshead rate of 0.305 mm/min (0.012 in./min) until a crosshead displacement of 2.5 mm (0.1 in.) compression (ASTM International 2022a) (Figure 1B).

Data processing and calculation methods

Load, displacement, and deflection gauge data were recorded throughout each test. Stress and strain were determined by $\sigma = F/A$ and $\epsilon = \Delta L/L$, where F is the force measured by the crosshead, A is the measured cross-section of the loaded area of the specimen (i.e., the bearing plate width multiplied by the specimen width), ΔL is the deformation measured by the deflection gauge, and L_i is the initial depth of the specimen.

Yield stress in compression perpendicular to the grain was calculated using four standardized methods for calculating compressive strengths: visual determination, the point on the stress-strain curve where the angle between the stress-strain curve and y-axis increases by 50% (ISO 13061-5), the intersection point of the 1% offset of the linear elastic region (EN 408), and the intersection between the linear elastic region and a line fit to the plastic region (EN 12512) (British Standards Institution 2005; British Standards Institution 2012; International Organization for Standardization 2020). While ISO 13061-5 defines the stress at the proportional limit and EN 408 defines the compressive stress, this study applies the methodology as a yield stress calculation.

Modulus of elasticity calculation

To facilitate a simplified and automated analysis procedure, the slope of the linear elastic region was defined using consistent load intervals across all samples. Visual inspection indicated that the linear region generally occurred at loads between 30% and 50% of the maximum load. As such, the modulus of elasticity was defined as:

$$MOE_{\perp} = \frac{0.5f_u - 0.3_{fu}}{0.5\epsilon - 0.3\epsilon} \quad [3]$$

Yield stress calculation

Visual method

As implied by the name, the visual method requires that the user define the yield stress visually on the stress-strain curve as the upper limit of the linear-elastic regime. After selecting a point, the algorithm selects the closest recorded data point and defines the corresponding stress as the yield stress.

ISO 13061-5

ISO 13061-5 defines the load corresponding to the proportional limit "as the ordinate of the point where the tangent of the angle formed by the load axis with the tangent to the load-deformation curve is 50% greater than its value in the linear portion of the diagram." The linear portion corresponds to the

elastic region; therefore, its slope is taken as the perpendicular modulus of elasticity, $MOE_{\perp}$ The angle of the elastic region relative to the load axis was defined as:

$$\theta_1 = \tan^{-1}\left(\frac{1}{MOE_{\perp}}\right) \quad [4]$$

In accordance with ISO 13061-5, the angle of the tangent line at which the compressive strength is defined was defined as: $\tan(\theta_2) = 1.5\ \tan(\theta_1)$(Figure 2) (International Organization for Standardization 2020).

EN 408

EN 408 defines the compression strength perpendicular to the grain using an iterative process. First, an initial estimate of the yield stress on the stress-strain curve, $F_{C,90,max}$ is selected. The algorithm then determines $0.1F_{C,90,max}$ and $0.4\ F_{C,90,max}$, identifies where these values intersect the stress-strain curve, and calculates the modulus of elasticity as:

$$MOE_{\perp} = \frac{0.1\ \sigma - 0.4\sigma}{0.1\epsilon - 0.4\epsilon} \quad [5]$$

A line with the slope $MOE_{\perp}$ is then drawn offset on the x-axis by the strain corresponding to a deformation of $0.01h$, where h is the original height of the test specimen. The intersection of this offset line and the stress-strain curve is calculated to determine $F_{C,90,max,est}$ (Figure 3). If $F_{C,90,max,est}$ is within 5% of $F_{C,90,max}$, then $F_{C,90,max}$ may be used as the compressive strength. The procedure is repeated until a value within the tolerance is found (British Standards Institution 2012).

EN 12512

EN 12512a defines the yield load for load-displacement curves exhibiting two well-defined linear regions as the intersection point between two lines drawn parallel to these respective regions. To simplify and automate analysis, the slopes of the lines were defined by consistent regions across all samples. Visual inspection indicated that the first linear region was generally observed at loads between 30% and 50% of the maximum load, while the second linear region typically occurred between 90% and 99% of the maximum load. As such, the slopes were defined by:

$$m_1 = \frac{0.5F_u - 0.3_{F_u}}{\delta_{0.5} - \delta_{0.3}} \quad [6]$$

$$m_2 = \frac{0.99F_u - 0.9F_u}{\delta_{0.99} - \delta_{0.9}} \quad [7]$$

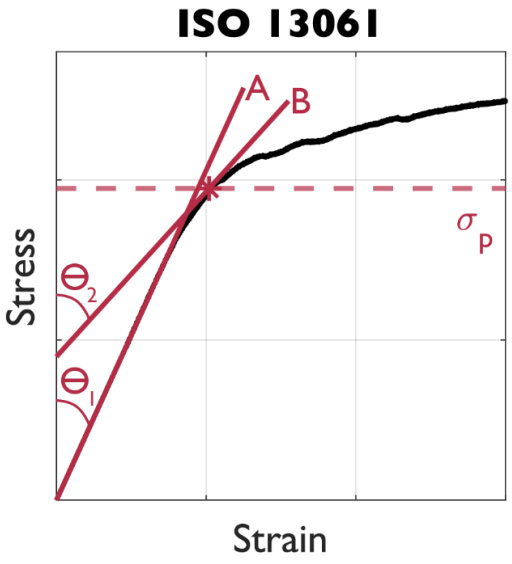


Figure 2. A depiction of the method for calculating the compressive perpendicular to grain strength at the proportional limit outlined in ISO 13061.

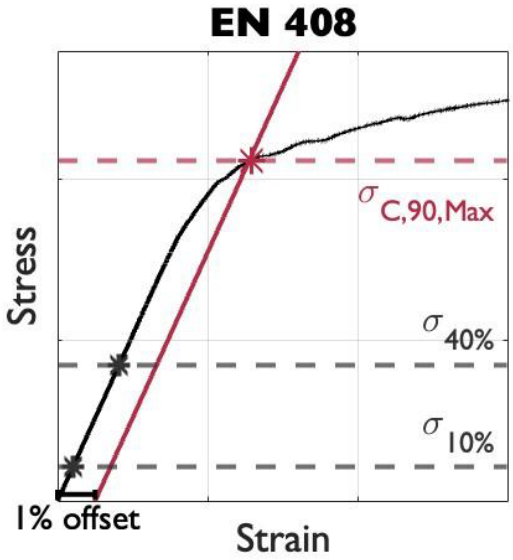


Figure 3. A depiction of the method for calculating compression stress perpendicular to the grain outlined in EN 408.

where F_u is the maximum load for each sample and δ represents the corresponding displacement (British Standards Institution 2005).

EN 12512b provides a method for defining the yield load for load-displacement curves that do not exhibit two well-defined linear parts. The yield load is determined by the intersection of two lines. The first line is drawn through the points of the load-displacement curve corresponding to $0.1F_u$ and $0.4F_u$ The second line has a slope equal to 1/6 of the slope of the first line and is tangent to the load-displacement curve (British

Standards Institution 2005). Refer to Figure 4 for visualizations of both EN 12512a and EN 12512b.

Statistical Analysis

The average, standard deviation, and coefficient of variation of the yield stresses were calculated for each of the four methods. The processed data was used for all calculation methods. A one-way analysis of variance (ANOVA) test was performed ($\alpha = 0.05$ significance level) to determine whether there were significant differences between the calculated yield stress values from each of the four methods utilized. Resulting yield stresses were plotted on a histogram, and a Weibull probability-density function was fitted to the data to assess spread.

Results

Literature review

Fifty-four papers were deemed relevant to the literature review, meaning they tested small wood specimens in compression perpendicular to the grain and calculated a compressive stress value (Ido et al. 2010; Widmann et al. 2012; Barnes et al. 2013; Moya et al. 2013; Pleschberger et al. 2013; Skarvelis and Mantanis 2013; Ang et al. 2014; Jiang et al. 2014; Yorur et al. 2014; Crafford and Wessels 2016; Hong et al. 2016; Kotlarewski et al. 2016; Milch et al. 2016; Tippner et al. 2016; Bahtiar et al. 2017; Kiaei and Abadian 2018; Lukowsky et al. 2018; Miyamoto et al. 2018; Chen et al. 2019; M Hussein et al. 2019; MM Hussein et al. 2019; Kijidani et al. 2019; Pang et al. 2019; Irby et al. 2020; Kovryga et al. 2020; Müller et al. 2020; Roszyk et al. 2020; Uzcategui et al. 2020; Verbist et al. 2020; Muthumala et al. 2021; Sharma and Kelkar 2021; Shmulsky et al. 2021; Bahtiar et al. 2022; Cheng et al. 2022; Cherry et al. 2022; Collins and Fink 2022; Kurt and Korkmaz 2022; Piernik et al. 2022; Smídová et al. 2022; Wu et al. 2022; Yu et al. 2022; Zhang et al. 2022; Feujofack K and Loss 2023; Gupta et al. 2023; Shukla and Viswanath 2023; Fruehwald-Koenig and Heister 2024; Marasigan et al. 2024; Mendes et al. 2024; Neimsuwan et al. 2024; Rosner et al. 2024; Toba et al. 2024; Gambarelli et al. 2025; Ike et al. 2025; Naissi et al. 2025; Saltik 2025). Papers focused on composite materials or engineered wood products were excluded, as the goal of this review was to characterize common testing and analysis methodologies for clear wood. Similarly, papers reporting finite element simulations rather than experimental testing were excluded. The following results summarize the testing and strength calculation methodologies employed across the 54 relevant papers. Many studies include multiple measurements of compressive strength (e.g., reporting the stress at 5% strain and the stress at the proportional limit), and these are considered as independent in the summaries below. As such, the total number of papers reported in Table 3 and the following paragraphs may not sum to the expected total number of papers.

Geographically, the papers spanned six continents: 3 were written by primary authors based in Africa, 23 in Asia, 3 in Australia, 18 in Europe, 5 in North America, and 2 in South America.

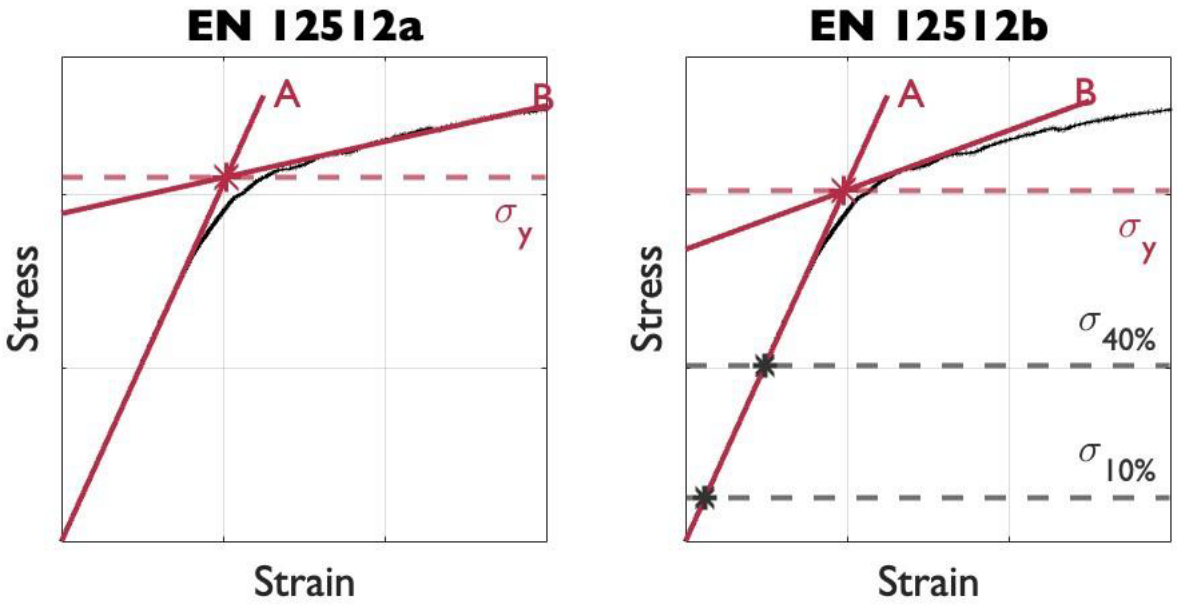


Figure 4. A depiction of the methods outlined for calculating the yield load described in EN 12512.

Due to variations in calculation and testing methods, the standard used for material testing was considered separately from the standard or method used for compressive strength analysis. Table 3 shows the testing standards used in the papers reviewed: 19 papers cite ASTM D143, 6 cite EN 408, and 4 cite ISO 13061-5. Twelve additional testing standards are cited for material testing. Two papers do not cite any standards for material testing.

Of the 54 papers in the literature review, 34 specified how the compressive strength was determined and 20 papers did not indicate any calculation procedure. Of the 34 papers discussing analysis methodology, 14 papers cited a standard used for analysis (AS/NZS 4063 – 2, ASTM D143 – 1, BS 373 – 1, DIN 52192 – 1, EN 408 – 5, ISO 13061-17 – 2, ISO 13910 – 1, ISO 3132 – 1, JIS Z2101 – 1), and 20 papers specified a method for analysis but did not link that to a standard (British Standards Institution 1957; International Organization for Standardization 1975; German Institute for Standardization 1979a; Japan Standards Association 1994; Standards Australia and Standards New Zealand 2010; British Standards Institution 2012; International Organization for Standardization 2014; International Organization for Standardization 2017; ASTM International 2022a). The discussion of the analysis methods used in the literature will focus on papers utilizing ASTM D143, EN 408, and ISO 13061-5 for test methodology (British Standards Institution 2012; International Organization for Standardization 2020; ASTM International 2022a). Table 4 provides an overview of the analysis methods utilized by those papers.

Nineteen papers utilized ASTM D143 for material testing (Table 4) (ASTM International 2022a). This standard does not specify a method for determining the stress of wood in compression perpendicular to the grain. Only nine of these papers specified the methodology used to determine the compressive stress of the wood. Two papers calculated the stress as the proportional limit on the stress-strain curve: one of these papers cited ISO

Table 3. Testing standards for compression perpendicular to the grain cited in the reviewed literature.

Testing standard	Number of papers	Standard's region of development	Country of first author
ASTM D143 (ASTM International 2022a)	19	USA	Australia, Canada, Egypt, Germany, Indonesia, Iran, Korea, Philippines, Portugal, Thailand, United Kingdom, United States, Uruguay
EN 408 (British Standards Institution 2012)	6	Europe	Brazil, Czech Republic, Finland, Germany, Spain
ISO 13061-5 (International Organization for Standardization 2020)	4	Global	China, Japan, Poland
BS 373 (British Standards Institution 1957)	4	UK	Czech Republic, Malaysia, Sri Lanka
DIN 52192 (German Institute for Standardization 1979a)	4	Germany	Austria, Germany, Switzerland
IS: 1708 (Indian Standards Institution 1986)	3	India	India
GB/T 1943–2009 (National Standards of People's Republic of China 2009a)	2	China	China
ISO 13061-17 (International Organization for Standardization 2017)	2	Global	Turkey
JIS Z2101 (Japan Standards Association (JSA) 1994)	2	Japan	Japan
AS/NZS 4063 (Standards Australia and Standards New Zealand 2010)	2	Australia/New Zealand	Australia, South Africa
GB/T 1939-2009 (National Standards of People's Republic of China 2009b)	1	China	China
DIN 52185 (German Institute for Standardization 1979b)	1	Germany	Germany
ISO 3132[1] (International Organization for Standardization 1975)	1	Global	Greece
TS 2473 (Turkish Standards Institution 1976)	1	Turkey	Turkey
Unspecified Chinese national standard	1	China	China
No standard specified	2	N/A	Austria, China

[1] ISO 3132 has been replaced by ISO 13061.

Table 4. Analysis methodologies utilized by papers citing ASTM D143, EN 408, and ISO 13061-5 as the standard test methodology.

Testing standard	Analysis method	Analysis standard cited	Number of papers
ASTM D143	None specified	None	10
	Fixed displacement	AS/NZS 4063	1
		ASTM D143	1
		ISO 3132	1
		None	2
	Proportional limit	ISO 3132	1
		None	1
	Maximum displacement	None	3
	Linear offset	EN 408	1
	Novel method	None	1
EN 408	None specified	None	2
	Linear offset	EN 408	4
ISO 13061-5	None specified	None	1
	Proportional limit	None	2
	Fixed displacement	None	1
	Novel method	None	1

3132 for this calculation, and the other did not cite an analysis standard (International Organization for Standardization 1975). Three papers calculated the stress as the maximum force over the area of the specimen; none of these papers cited an analysis standard. One paper calculated the stress using a linear offset method and cited EN 408 as the analysis standard (British Standards Institution 2012). One paper utilized a novel method to calculate the stress. Five papers calculated the stress at a fixed displacement: one did so according to AS/NZS 4063 at 0.1 times the height of the specimen, one did so according to ISO 3132 at 2.5 mm deflection, and one did so at 1 mm deflection, citing ASTM D143, despite this not being specified in the standard. The remaining two papers did not cite an analysis standard, but one calculated the stress at 1 mm and the other at 2.5 mm (International Organization for Standardization 1975; Standards Australia and Standards New Zealand 2010; ASTM International 2022a). The 2.5 mm displacement corresponds with the end of the compression perpendicular to grain test in specified ASTM D143 and the 1 mm displacement corresponds with serviceability stress definitions provided in ASTM D245, although the connection between the analysis methodology and the standards was not linked in these papers (ASTM International 2022a; ASTM International 2022b). Of the 19 papers utilizing ASTM D143 for material testing, 16 of those papers referred to the calculated strength property as the "strength," "compressive strength," or "compressive strength perpendicular to grain," without specifying whether this is a yield strength, ultimate strength, maximum strength, etc.

Seven papers cited EN 408 as the testing and/or the analysis standard (Table 4) (British Standards Institution 2012). One paper cited ASTM D143 for testing and EN 408 for strength analysis and four papers cited EN 408 for both testing and analysis (British Standards Institution 2012; ASTM International 2022a). Two papers cited EN 408 only for testing and did not specifically discuss a method of analysis; however, this does not necessarily mean a different analysis method was used (British Standards Institution 2012). All seven papers referred to the calculated strength property using generic terms ("strength," "compressive strength," or "compressive strength perpendicular to grain").

Four papers cited ISO 13061-5 as the standard used for material testing (Table 4) (International Organization for Standardization 2020). No papers explicitly stated that ISO 13061-5 was used for analysis as well, although the standard does provide a procedure for calculating the stress at the proportional limit. Of these four papers, two papers used the proportional limit as the compressive strength, one paper determined the compressive strength using a novel method similar to EN 12512 and a fixed displacement at 5% strain, and one paper did not specify an analysis method. Of the four papers utilizing ISO 13061-5 for material testing, three of those papers referred to the calculated strength property using generic terms (British Standards Institution 2005; International Organization for Standardization 2020). Two additional papers utilized ISO 13061-17 for material testing in compression perpendicular to

the grain, calculating the strength as the maximum load over the cross-sectional area, though this standard was developed for compression *parallel* to the grain (International Organization for Standardization 2017).

The literature review demonstrates that several different methods are being used to determine the compressive strength of wood in compression perpendicular to the grain, and no single method seems to be dominating the current literature. Even within a set of papers utilizing the same material testing standard, multiple methods will be used to calculate the compressive strength that may yield drastically different values. The literature review also highlights the need for consistent and clear language when referring to and defining compression strength. This is particularly important for compressive strength perpendicular to the grain, given that the published standards and literature define strength at specified deformation or strain, the proportional limit, the ultimate strength, and/or the yield strength. The high number of papers using ASTM D143 test procedures highlights the need for a standard analysis approach.

Experimental results

Processed stress-strain profiles for the 18 spruce-pine-fir samples are shown in Figure 5.

The mean compression perpendicular to grain modulus of elasticity was 374 ± 136 MPa. The coefficient of variation was 36.28%.

Table 5 contains the mean and standard deviation compressive perpendicular to grain yield stress values for the four methods utilized in addition to the coefficient of variation. The mean yield stress was lowest for the ISO 13061-5 calculation (4.926 MPa) and highest for the EN 408 calculation (6.448 MPa).

Figure 6 provides the results of a single specimen's stress-strain curve to visually represent the different yield points selected by the different methods. The ASTM deformation serviceability limit is also indicated.

Performing an analysis of variance (ANOVA) test indicates that yield stress values resulting from the different calculations

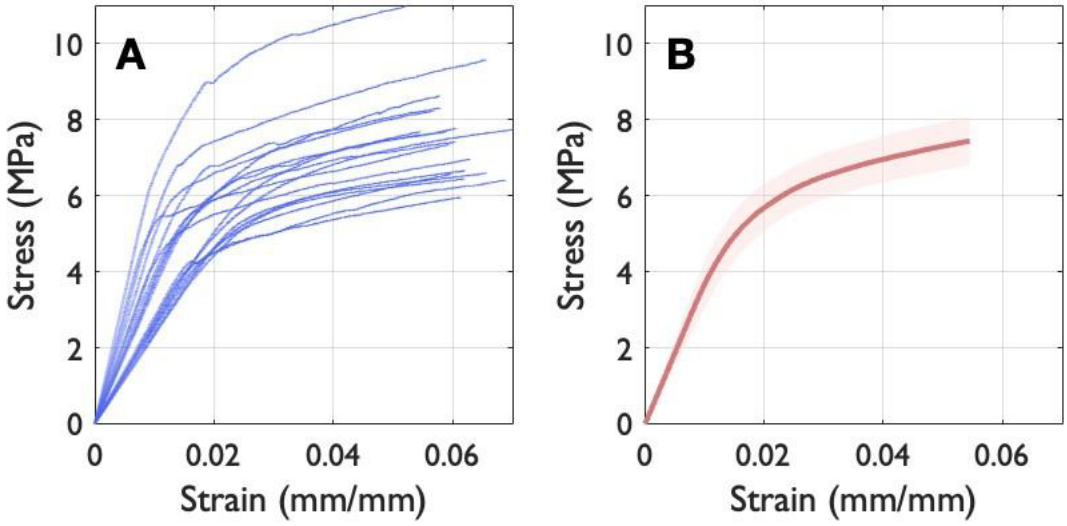


Figure 5. (A) processed stress-strain profiles; (B) mean stress-strain profile with 95% confidence interval.

Table 5. Yield stress values for the four methods tested.

Method	Mean (MPa)	Standard Dev (MPa)	Coefficient of Variation (%)	Maximum (MPa)	Minimum (MPa)
Visual	5.549	0.923	16.63	7.825	4.321
ISO 13061-5	4.926	0.682	13.845	6.180	3.943
EN 408	6.448	1.0741	16.66	9.450	4.941
EN 12512a	6.270	1.077	17.17	9.513	4.818
EN 12512b	5.759	0.930	16.14	8.204	4.396

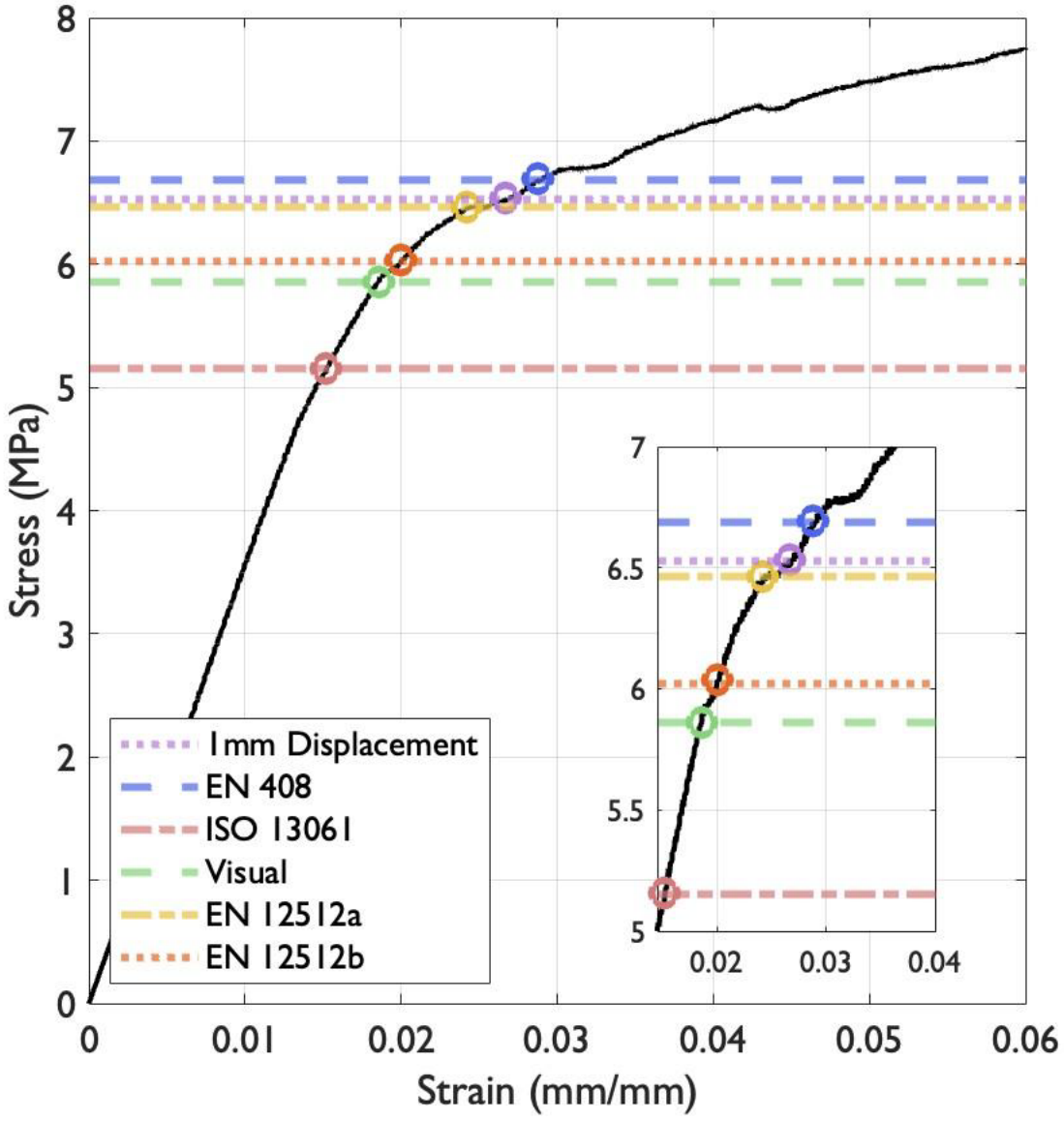


Figure 6. The stress-strain curve of Sample 01A with the resulting yield stresses from the four methods utilized.

methods are significantly different ($p < 10^{-5}$). Figure 7 shows the histogram of yield stresses for each calculation method with a two-parameter Weibull probability-density function fit to each curve. A two-parameter Weibull distribution was selected to align with procedures outlined in ASTM D5457 (ASTM International 2023).

A separate calculation of the stress corresponding to the 1 mm deflection, the ASTM serviceability limit, resulted in a mean stress of 6.295 ± 1.221 MPa (coefficient of variation = 19.39%) (Figure 8). This value most closely aligns with the mean yield stress calculated using EN 12512a (British Standards Institution 2005).

Discussion

This experimental campaign and research investigation characterized differences between international standards for defining compression strength perpendicular to the grain. The literature review showed that there is no dominant method for determining compressive stress and that there is a disconnect between testing and analysis methods. Of the 54 papers reviewed, only 34 provided explicit insight into how the compressive stress was calculated. Within sets of papers utilizing the same material testing standard, multiple methods were used to calculate compressive stress. The experimental campaign evaluated five methods for determining yield stress and found that the methods provided statistically different stress values. Thus, an

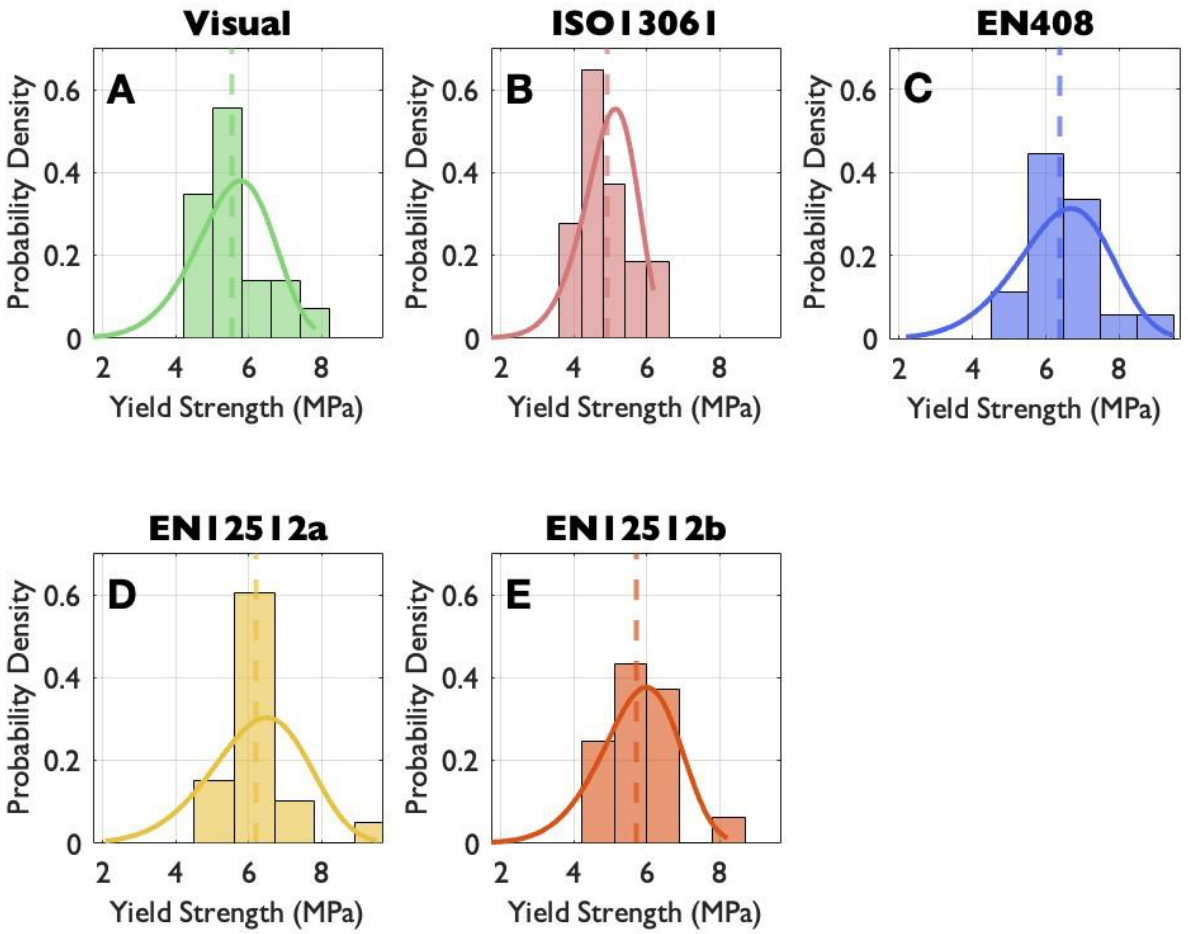


Figure 7. Histograms of the yield stress values with an overlayed Weibull probability-density function and average strength indicated by a dashed line for the (A) visual method, (B) ISO 13061-5, (C) EN 408, (D) EN 12512a, and (E) EN 12512b.

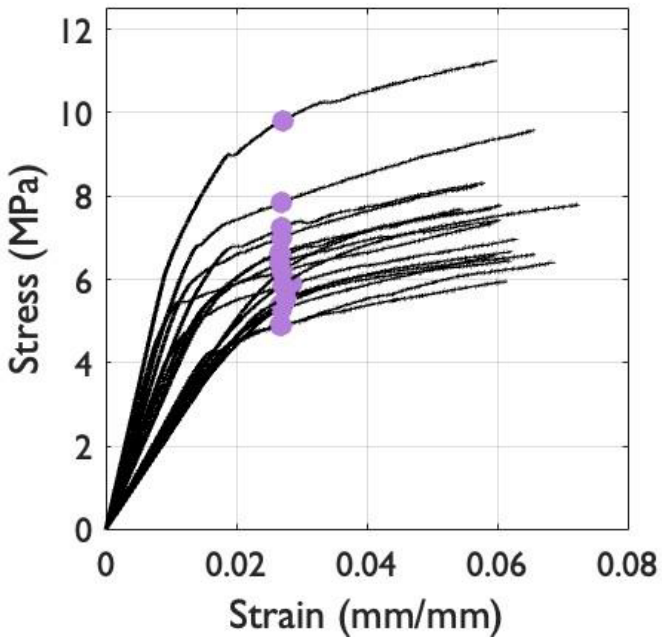


Figure 8. The stress-strain curves with the point of 1 mm deflection indicated as a purple circle.

analysis method must be standardized to allow for reproducible results, especially to be used with ASTM D143, which does not provide a calculation method for determining the yield stress in compression perpendicular to the grain (ASTM International 2022a).

The significant differences in the stress calculated by the analysis methods may reflect the different material properties that each standard was developed to determine. ISO 13061-5, which produced the lowest mean strength, determines the "proportional limit" stress (International Organization for Standardization 2020); this is consistent with the proportional limit representing the beginning of non-linear behavior on the stress-strain curve. EN 12512 determines the "yield" stress, and the two methods specified produced average stresses higher than ISO 13061-5 (British Standards Institution 2005); this is expected because the yield stress is often an engineered calculation that lies above the first instance of non-linear behavior. EN 408, which produced the highest mean stress,

determines the "compression strength." Since the standard defines the load at this strength as the "maximum load," it is expected that this method would produce the highest strength calculation (British Standards Institution 2012).

For reproducibility of analysis, comparison of results, and efficient data processing, it is advantageous for analysis methods to be automated. While the visual method enables each sample to be analyzed independently, the introduction of human engineering judgement can lead to differences in results. Similarly, EN 408 requires engineering judgement for the initial estimate of yield stress to perform the analysis. This human interaction for each sample also reduces the efficiency of data analysis, which is essential for highly heterogenous materials like wood which require large sample sizes. EN 12512, by contrast, is a fully automated procedure (British Standards Institution 2005). While it was not developed for use in compression perpendicular to grain tests, it leads to results that are within range of methods developed for this application while requiring limited human input. As such, EN 12512 provides a standardizable procedure for calculating the yield stress of clear wood perpendicular to grain for tests performed in accordance with ASTM D143.

An additional method proposed by Christensen was considered but ultimately excluded from the analysis (Christensen 2008). This method identifies the yield point as the absolute maximum of the second derivative of the stress-strain curve, corresponding to the point at which the tangent modulus changes at the greatest rate with respect to increasing strain (Christensen 2008). In practice, however, numerical differentiation of experimental data produced unreliable results. Noise in the data led to local negative slopes in the elastic region, despite a globally constant and positive slope. A similar challenge was found when applying the methods of ISO 13061-5 using numerical integration (International Organization for Standardization 2020). Smoothing approaches such as the Savitzky-Golay filter were sensitive to parameter selection, with different parameter choices leading to meaningfully different results. Because this study aimed to develop a methodology that could be applied consistently regardless of data sampling rate, this method was deemed not viable.

The methodologies in EN 12512 are recommended for adoption into the North American practice for defining yield stress (British Standards Institution 2005). It offers a fully automated, analytically efficient procedure, suitable for the large sample sizes required for heterogenous materials like wood. Specifically, EN 12512a provides the most appropriate yield stress calculation method for integration with ASTM D143. ASTM D143 ends testing after 2.5mm of deflection and, given the linear post-yield behavior of most softwood lumber, this would result in a stress-strain curve with two well-defined linear parts (ASTM International 2022a). In that case, EN 12512 specifies method a. Method b would instead be used for a longer-term loading, which is irrelevant when using ASTM D143 testing procedures (British Standards Institution 2005; ASTM International 2022a). Additionally, EN 12512b requires a calculation of the line tangent to the stress-strain curve, which can be computationally challenging and sensitive to noise and data filtering techniques. EN 12512a, thus, provides a fully automated method for determining yield stress that compliments the compression perpendicular to grain testing procedure outlined in ASTM D143.

Conclusion

The yield stress is an essential material property for integrating stress-strain behavior into computational modeling. However, ASTM D143 does not specify a method for calculating the yield stress of wood in compression perpendicular to the grain (ASTM International 2022a). A literature review of 54 papers reveals that no dominant method has been established for determining strength in compression perpendicular to the grain, and testing methods can often be misaligned with analysis procedures. Many papers reviewed utilizing ASTM D143 testing procedures do not specify the analysis method used and use generic language to describe the strength, further highlighting the need to standardize calculation procedures.

This paper compared four different analysis methods for defining compression perpendicular to grain yield stress: the visual method (implied by ASTM D143), ISO 13061-5, EN 408, and EN 12512. The visual method, implied by ASTM D143, and ISO 13061-5 are intended for small, clear wood samples, while EN 408 is intended for structural-scale samples. EN 12512 is a standard test methodology for cyclic testing of mechanical joints in timber structures; however, its process for defining yield stress has been previously applied to clear wood compression strength in the literature. Compression perpendicular to grain tests were performed in accordance with ASTM D143 and analyzed utilizing methodologies outlined in several international testing procedures (ASTM International 2022a). ANOVA results indicated statistically significant differences in yield stresses across the methodologies, highlighting a need for a standardized yield stress calculation method in ASTM D143. The method outlined in EN 12512a is recommended for implementation with ASTM D143 testing proce-

dures as it provides a fully automated, analytically efficient yield stress calculation procedure that is not sensitive to data cleaning methods (British Standards Institution 2005; ASTM International 2022a).

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