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STRUCTURAL (PERFORMANCE) CLASS POTENTIAL FOR NORTH AMERICA

Eric Jones[1], David E. Kretschmann[2], Kevin Cheung[3]

ABSTRACT: Structural class systems are species-independent product classification systems for structural timber. They are used throughout the world to reduce the number of species and grade choices that face the designer of wood construction projects. Structural class systems offer an opportunity to simplify timber specification in North America and to encourage more effective quality standardization across product types. This report gives some background information on the development of major structural class systems used in other countries. The guiding principles of a new ISO Structural Class standard will be applied to develop a potential structural class system for use in North America. A structural class system tuned for the most commonly used strength and stiffness performance categories used in North America can simplify timber specification for design engineers and make wood construction more favourable to architects and engineers in their selection of construction systems among wood, concrete, and steel. It is suggested that the time for a structural class system in North American has finally come.

KEYWORDS: Structural Class, Timber, Dimension Lumber, Design Values, Strength, Stiffness, Stress Class

1 INTRODUCTION

In 1990 a publication targeting the North American dimension lumber industry asked the question- Stress Class Systems: An idea whose time has come? [1] Evidently the answer to the question at that time was no. North America doesn't yet have a Stress Class—also known as structural class—system for timber (the term "timber" is used here in the international sense and applies to all sizes of structural sawn wood products).

The North American timber market still utilizes a system of specification that supplies design values for at least 8 grades of approximately 50 species or species combinations resulting in over 400 possible species-grade combinations [2,3]. Although a structural class system is not a grading system and doesn't reduce the number of species-grade combinations, it does reduce the number of choices in design by grouping combinations together for the purpose of structural specification.

In principle, any timber grade can be grouped in a structural class system whether it is hardwood or softwood, visually or mechanically graded, solid sawn or composite timber. The only requirement is that the product has the properties specified for the applicable structural class.

Structural class systems have been used extensively in Europe and Oceania [4, 5]. An international standard is in the process of being adopted that provides guidance for setting up structural classes [6]. Using this standard as a tool it may now be possible to propose a Structural Class system that would support and expand wood construction in North America.

2 GENERAL METHOD

2.1 GUIDING PRINCIPLES

Basic principles guided the recent international structural class effort, including the following:

- Simplified material selection
- Sustained potential for end uses (product utility)
- Structural reliability

A simplified class system would greatly reduce the confusing number of options confronting a structural engineer when designing with wood. With the hundreds of combinations of size, grade, species and products, it is no surprise that timber is often overlooked for structural design.

[1] Eric Jones, consultant to the Canadian Wood Council, Canada. Email: eric.jones086@sympatico.ca
[2] David E. Kretschmann, UDSA FS Forest Products Laboratory, 1 Gifford Pinchot Dr., Madison, WI 53726, USA. Email: dkretschmann@fs.fed.us
[3] Kevin Cheung, Western Wood Products Association, USA Email: kcheung@wwpa.org

Although potential end uses for timber do not hinge solely on design values, they can be restricted in some cases by span or load capacity requirements. Efficient product utility cannot be ignored, as unused capacity is wasted resource.

Structural reliability is a goal for any material design framework and is mentioned in this context so that it is not forgotten in an effort to balance simplicity and product utility.

2.2 BASIC ASSUMPTIONS

Structural class systems are based on assumptions about populations, test data, and the grading system; i.e.:

- Primary property data should be based on characteristic values from full-size specimen testing,
- Flexural properties (MOR, MOE) are fundamental criteria in the structural class system,
- The MOR-MOE relationship is closely linked to variables of timber grading, sampling and testing,
- Other criteria such as density may be added, and there may be a role for quality control in checking such criteria, and
- Any grading system recognized in a structural class system needs to be well-tested and stable.

2.3 KEY DECISIONS

Structural class systems are based on the relationship between primary properties, usually modulus of rupture (MOR) and modulus of elasticity (MOE). The first decision in establishing a class system is how to characterize this relationship so that it will be broadly applicable to the appropriate timber products.

The next major decision area is to locate classes on an x-y grid for the primary properties. This raises two questions: how large to make the grid to cover the practical range for the products of interest, and how to divide the axes into discrete units to cover typical applications for the products.

Historically, methods such as ranking or a mathematical series have been used to establish structural class boundaries for the primary properties [7,8]. Practically, however, the final boundaries are generally shifted to arrive at consensus for each particular system's target market.

The primary property relationship is also used to develop correlations with derived properties to determine the rest of the values for the class system. This is the third decision area. Since these properties are derived from relationships to primary properties, greater efficiency is usually obtained in assigning the primary properties and it is necessary to consider the assignment method's potential effect on precision (or bias) for the derived properties.

3 PROPERTIES AND PROCEDURES

3.1 PRIMARY PROPERTIES

The MOE-MOR relationship is typically assumed to be a function of a measured correlation but each distribution can be very different, and while MOE is characterized by both a mean and a lower distribution limit, MOR is characterized by a lower limit only. Therefore, database and distribution assumptions can influence the relationship. The MOE-MOR relationship is closely linked to variables of timber grading, sampling and testing embodied in characteristic values. These variables should be identified and normalized in a structural class system or it will be difficult to allocate species and grades to classes in a consistent manner.

The MOE-MOR relationship is typically assessed by adjusting all MOR data to a characteristic product size basis, since MOR varies with size.

Linear regression equations of the form: $y = a + b(x)$ can be used to model the relationship between MOR and MOE. It should be noted that the relationship can depend on what sizes are being compared (steeper slope for wider widths), how the sampling and testing is conducted (random vs. 'biased' approach to positioning maximum strength-reducing characteristics, deformation measurements), sample size and other variables.

The relationship between characteristic lower 5th%ile MOR and mean MOE values for visually graded softwoods in the European EN structural class system can be expressed approximately as follows:

Eq.1 $$MOE_{EN} = 235(MOR_{05}) + 4670 \quad \text{[MPa]}$$

The slope and intercept are slightly different for visually graded hardwoods. Note that individual species coefficients will vary from those in this equation, although the slopes tend to be similar. Note also that these are characteristic value relationships, which are not the same as regressions on data distributions.

The ASTM approach to random location of maximum strength-reducing defects in the test span results in a higher strength estimate compared to the EN test method of placing these defects in the central third of the span, and the bending strength difference is estimated to range from 5% for high strength timbers to about 15% for lower strength timbers. On the other hand, the EN statistical method of calculating characteristic values results in higher strength property estimates. A review by Rouger in 2004 (ISO TC/165 N418) [9] suggested that these counterbalancing differences are approximately equal.

Note that different characteristic sizes in the EN and ASTM approaches (150 vs. 184 mm) and target moisture contents (12% vs. 15%) are further potential sources of difference, but they can be accounted for by appropriate data adjustments.

Bending test differences also influence MOE properties, so MOE tends to be somewhat lower in EN standards compared to ASTM standards (Note that the different target moisture contents have the opposite effect.). Test reports suggest that the magnitude of the test method difference is in the range of 5% for lower stiffness material and insignificant for higher stiffness material.

Provided the data is properly adjusted to the same standard conditions, the relationship in Eq. 1 seems to work for North American as well as European timber data. Figure 1 shows an example of characteristic value MOR and MOE data of North American species plotted along with a line representing the general relationship in the EN strength-class standard.

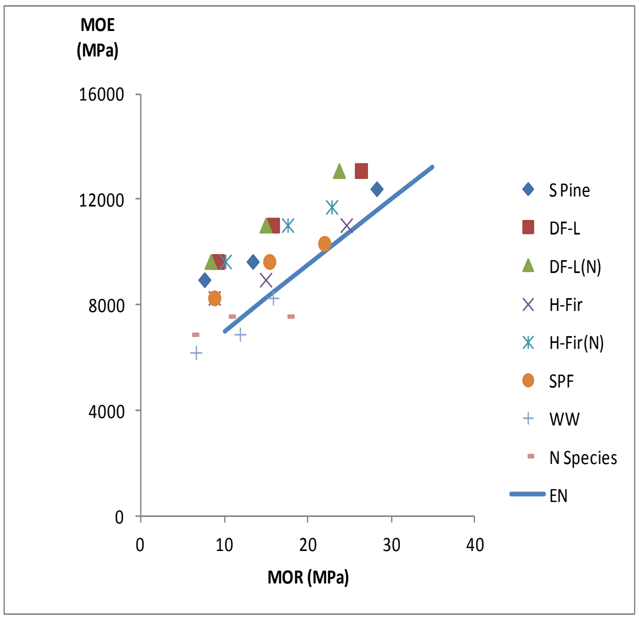

Figure 1: *Primary property relationships*

For machine-graded (MSR) timber, however, the slope tends to be steeper than for visually graded timber due to targeted strength properties and limits placed on the stiffness property. Machine-graded timber is designed to have a tighter ratio between the mean and 5% MOE values, a ratio that can change depending on the process. For North American MSR timber the MOR-MOE relationship can be characterized approximately as follows:

Eq.2 $MOE_{MSR} = 400(MOR_{05}) + 1000$ [MPa]

The relationship in Eq.1 is used in a general way to present draft options shown in the next section. An important caveat to this approach is that the relationships are derived on the basis of known grading systems with a long history of performance. New or modified grading systems may change these relationships.

Density is sometimes treated as a primary property, and it has an important relationship to the other primary properties. Figure 2 shows an example of the relationship between mean MOE for typical softwoods and mean density (expressed on an oven-dry basis).

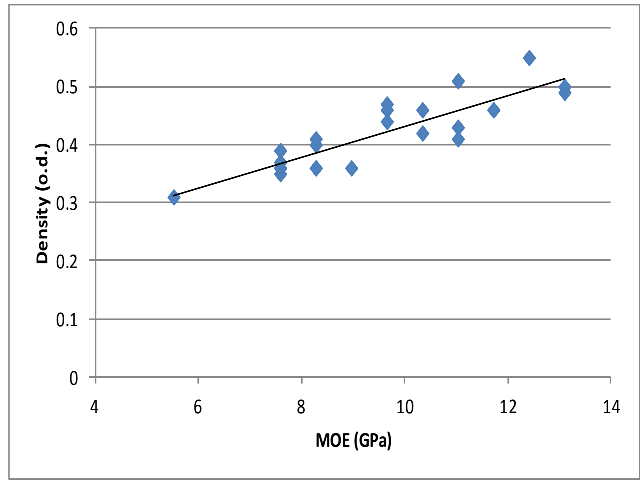

Figure 2: *Typical MOE-density relationship*

3.2 CLASS BOUNDARIES

Structural class systems can be derived from preferred number series using a geometric progression based on a common ratio from each level to the next (Green and Kretschmann, 1990; Booth, 1967) [1][10]. While a logical mathematical basis is desirable, class systems are often modified for practical reasons such as to accommodate significant product categories.

The preferred number approach results in increasingly wider intervals for higher class values In EN 338, for example, the MOR intervals range from 2 MPa at the bottom to 5 to 10 MPa at the top. This seems to imply a gradient in precision, as does the transition from single digit values to double-digit values.

Ideally material design values should imply a consistent level of structural reliability, such that all items are allocated with an appropriate degree of precision unless the intent is to provide exceptions in cases where a high degree of certainty about structural properties is required.

One method for investigating boundaries that convey this consistent level of reliability within a group is to conduct cluster analyses using traditional design values for various species or species groups. A cluster analysis provides a statistical grouping of products with similar properties. Figure 3 shows an example of boundaries that could be drawn for seven structural classes based on North American species.

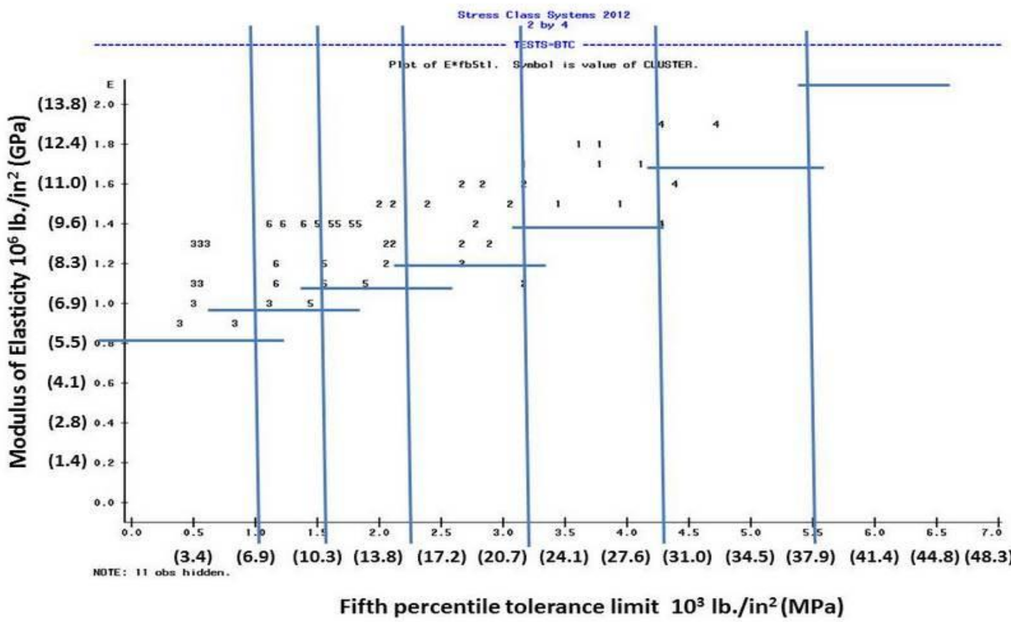

***Figure 3**: Example of cluster analysis (symbols identify similar cluster groups)*

There are other questions to be answered in setting up class boundaries in addition to statistical concerns; i.e.:

- Where is greater precision desired?
- How small should class divisions get before they are too fine to be differentiated in normal timber production and sorting practice?
- How much do class intervals affect end use?

Broader intervals between class divisions serve simplicity but could be less economical for product utility; on the other hand, finer intervals could be more difficult to maintain reliability over time. The problem is to find the right balance for class divisions.

One approach to the problem is to ask: what is the probability that a species-grade item would or would not re-qualify at a threshold value of varying class intervals; e.g. 1, 2, 3, 4 or 5 MPa? This is a complicated question linked to sample sizes and property distributions, among other things. It can be answered in a general way by comparing the probability of detecting a species difference of 1 to 5 MPa between populations that have similar distribution and variability.

Figure 4 below illustrates the relative stability of 5th %ile strength differences ranging from 100 to 600 psi (approximately equal to 1 to 4 MPa) for simulated sample sizes ranging from 100 to over 1000 specimens of two species. The simulation measures the statistical likelihood (power) that these differences in the underlying population will be present in a given sample.

The Figure suggests that a sample size of over 200 pieces might be required to regularly detect 5th%ile strength property differences of 4 MPa, and over 600 pieces for differences of 2 MPa. This is just a simulation, but it provides a general perspective on the question.

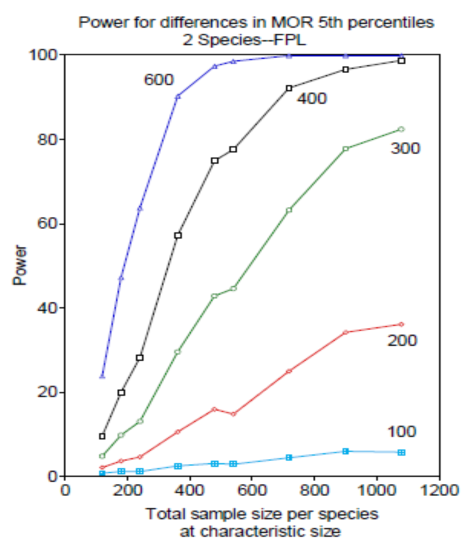

***Figure 4:** Simulation of strength differences*

3.3 DERIVED PROPERTIES

The basic assumption for derivation is that it is possible to establish species-independent relationships for the purposes of standardization, recognizing that the result will not always be optimal for all timber populations. Derived property options are discussed based on an assumed relationship between bending and axial properties. Structural comparisons between properties and procedures from different countries are complicated by questions of compatibility of data.

Relationships between axial and bending properties are reported by a number of sources [11,12,13,14] and shown as regressions between axial properties and either bending stiffness (MOE) or bending strength (MOR). Axial properties include ultimate tensile strength (UTS) and ultimate compressive strength (UCS) parallel to grain.

For the standardization purposes, MOR is typically used to predict axial properties to help control variables such as species- and size-dependency in property relationships. Strength properties can vary significantly with size, while MOE is generally considered to be size-independent. Both MOE and MOR also vary with species, but this can be "normalized" to some extent in strength properties by using a ratio (e.g. UTS/MOR or UCS/MOR) instead of the property itself as the dependent variable.

Figure 5 shows relative compression and bending data for a typical softwood timber distribution at a characteristic depth of 184 mm, compared to a trend line. Figure 6 shows relative tension and bending data for a typical softwood timber distribution at a characteristic depth of 184 mm, compared to a trend line.

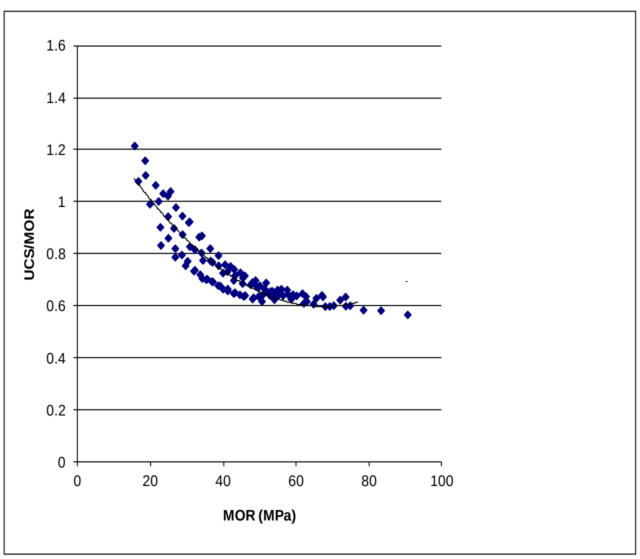

Figure 5: *Typical UCS/MOR property relationship*

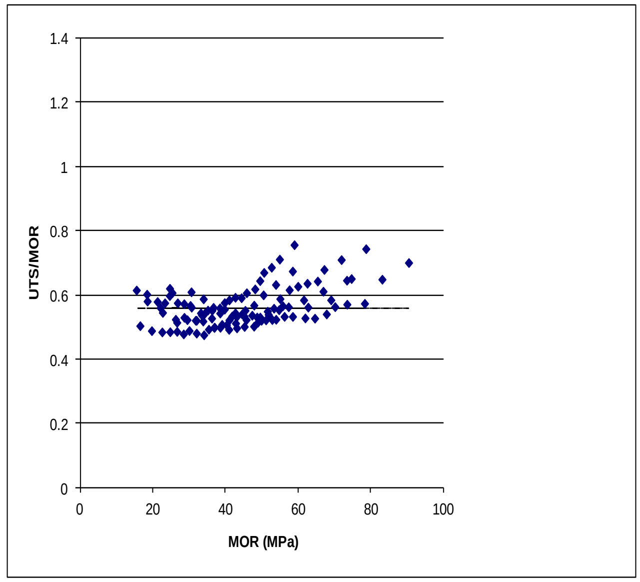

Figure 6: *Typical UTS/MOR property relationship*

Relationships for other properties such as shear and compression perpendicular to grain tend to be less consistent particularly for data derived from different testing and analysis methods. Data distributions are less meaningful for these properties, since they are based on small clear wood testing methods; instead, discrete data points for a number of species are presented, and reasonable estimates are derived from the property relationships.

Shear strength (USS) is considered to be independent of grade characteristics such as knots and slope of grain. However, it can still be estimated in a similar fashion to the axial/bending graphs. Figure 7 shows 5th%ile shear and bending data, based on small clear wood shear tests, with a polynomial trend line.

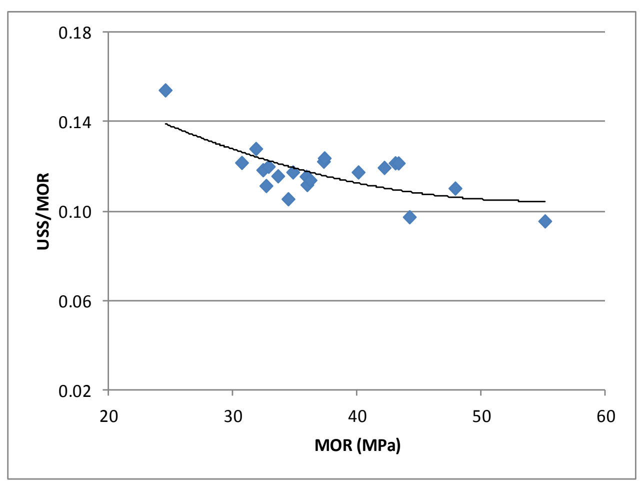

Figure 7: *Typical USS/MOR property relationship*

Compression perpendicular to grain is also measured by small clear testing and is related more closely to density than to other strength properties. It is also characterized as a mean value in North American standards, in contrast with other strength properties that are characterized as lower bounds (e.g., 5th percentile values). Although there is variation, the relationship is not size-dependent and can be shown directly between the two properties.

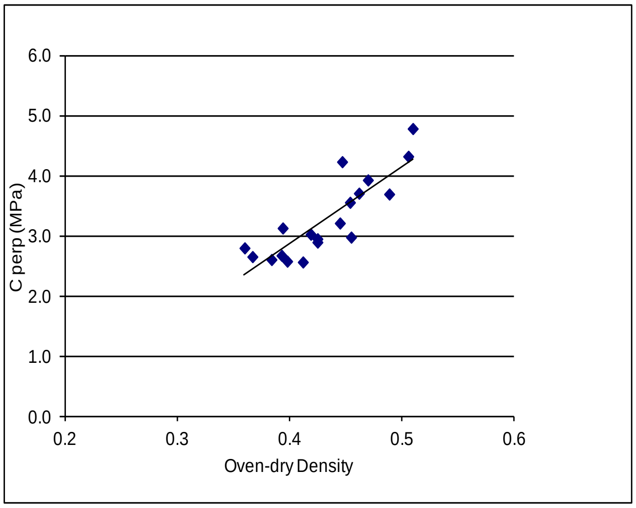

Figure 8: *Typical compression perpendicular to grain/ density relationship*

The property relationships described above may not apply to machine-graded timber grades and sizes. For one thing, there's a difference in the way property relationships are affected by visual and machine grading processes, and some property modes may be more or less related to size effects. These relationships need to be reviewed before finalizing a structural class system that includes machine-graded products, and before allocating machine-graded timber to classes in the system.

4 IMPACTS OF STRUCTURAL CLASS SYSTEMS

4.1 SIMPLIFICATION OF DESIGN PROCESS

Simplification results from a uniform set of design values being applicable to all members of a specified class. Building designers and specifiers will be familiar with these values and will also benefit from knowing that an appropriate product will be available for projects despite supply or manufacturing issues, and that designs will not have to be reworked to suit available products.

This is comparable to structural design in other materials, such as steel beams, and is an integral part of commercial building design practice.

There are also parallels in other wood products; for example, "Performance Rated" (APA trademark) wood I-joists. Although each wood I-joist manufacturer develops design values based on proprietary test data, "Performance Rated" I-joists are designed to have the same span for the same depth of I-joist, regardless of manufacturer.

Wood panel products can also be span-rated, such that typical products are interchangeable regardless of manufacturer.

A word of caution: having the same design values doesn't necessarily mean any product can be substituted for any other product in all cases. For example, substitution may be limited by other properties that are relevant to the end use but not assessed through the design standard, or by conditions that are placed on the resource or manufacture of commercial products.

4.2 PRODUCT UTILITY

Structural class systems can lead to some inefficiency where a product's capacity exceeds the level of design values assigned to a particular class. Yet some properties have to be classified at lower levels to achieve a workable system.

But this efficiency loss may be unimportant in applications where the capacity is not really needed. There are many instances where timber properties are not fully exploited by design; e.g.:

- Bending strength for joist or rafter designs that are governed by bending stiffness,
- Bending stiffness for truss chords that are stressed principally in axial modes, and
- Bending and tension strength in wall studs.

In setting up a structural class system, it is important to be aware of performance levels in relation to end use applications. The European system currently includes 12 softwood timber classes, of which just two or three (e.g. C18 and C24) are commonly specified and used. For most structural applications, a few classes are sufficient.

Similarly, No.2 grade is the most common softwood grade specified in North America and, although that single grade yields an array of structural properties from different species, the differences between No.2 design values for the major species combinations are not great. Again, the properties are sufficient for most structural applications, and machine-graded timber is available when greater capacities are required.

One further way to protect product utility is to offer a dual track for determining design values: 1) through structural classes, and 2) through individual species-grade design values.

4.3 STRUCTURAL RELIABILITY

The method for establishing design values for visually-graded dimension lumber in North America is based on testing a sample of full-size specimens "in-grade" as produced from the full geographic range of production, and establishing a design value on the basis of the lower part of the distribution of this sample.

This method of determining design values is more accurate than earlier methods extrapolated from tests of small, clear, straight-grained pieces of wood. However, this more comprehensive approach to sampling and testing introduces more technical issues and variables, and that can influence evaluation and assessment of structural properties over time.

Sources of variation in the structural properties of timber include changes in resource, seasonal logging and cutting practices, production processes, sorting and grading methods, and sampling and testing error. Some of the variation is expected and is a normal part of the product's performance over time. But eventually, significant changes might occur and lead to revisions in design values.

The introduction of a structural class system in North American design standards such as the National Design Specification (NDS) provides another avenue to moderate impacts of such changes by providing performance-based classes to represent a band of choices that are less sensitive to small changes in material properties.

EXAMPLE

The following example shown in Table 1 is based on a new ISO standard (ISO/DIS 16598) that is in final stages of approval, with a couple of adjustments to North American design assumptions.

The derived property values are determined from relationships that are lower than the mean trend lines shown in the Figures above, but are above the lowest limit of the relationships. The lowest limit approach would apply if there was less knowledge and experience about the resource and timber production and grading processes.

Note that the strength values in Table 1 are expressed on a characteristic value basis (lower exclusion limit) rather than allowable stress basis; therefore, the strength values are approximately twice that used in allowable strength design.

Table 1 Example of structural class system (softwoods)

Class	**F10**	**F16**	**F20**	**F24**	**F28**	**F32**	**F36**
Bending (MPa) F_b	10	16	20	24	28	32	36
Tension Parallel (MPa) $F_{t,0}$	5	8	11	13	15	17	19
Tension Perp. (MPa) $F_{t,90}$	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Compression Parallel (MPa) $F_{c,0}$	13	17	19	21	22	22	23
Compression Perp. (MPa) $F_{c,90}$	2	2.5	3	3.5	3.5	4	4.5
Shear (MPa) F_v	1.5	2.5	2.5	3	3	3.5	3.5
Mean MOE (GPa) E_{mean}	7	8.5	9.5	10.5	11.5	12.5	13.5
Density (g/cm^3) $P_{mean,o.d.}$	0.33	0.36	0.39	0.41	0.44	0.46	0.49

Notes to Example Table 1:

The values in this table were determined on a 150-mm width basis for softwoods using the following equations:

Eq. 3 $E_{mean} = 250\ (F_b) + 4500$ [MPa]

Eq. 4 $\rho_{mean} = 0.025\ (MOE) + 0.15$ [g/cm3]

Eq. 5 $F_{t,0} = 0.53\ (F_b)$ [MPa]

Eq.6 $F_{c,0} = F_b\ (1.7 - 4.6 \times 10^{-2}(F_b) + 4.6 \times 10^{-4}\ (F_b)^2\ )^*$ [MPa]

Eq.7 $F_{c,90} = (15\ (\rho_{mean}) - 3.3)$ [MPa]

Eq.8 $F_v = F_b\ (0.2 - 4.3 \times 10^{-3}(F_b) + 4.0 \times 10^{-5}(F_b)^2\ )$ [MPa]

Eq.9 $F_{t,90} = 0.5$ [MPa]

* Note: $F_{c,0}$ not permitted to be greater than 0.59 (F_b)

5 CONCLUSIONS

Structural classes are functioning efficiently in Europe and elsewhere. A Structural Class system tuned to the most commonly used strength and stiffness performance categories used in North America can simplify timber specification, will simplify the number of possibilities facing a design engineer, and make wood construction more favourable to architects and engineers in their selection of construction systems among wood, concrete, and steel. It is suggested that the time for a Structural Class system in North American has finally come.

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