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EFFECT OF VARIABILITY ON LUMBER DESIGN VALUES

Building designers, registered design professionals should stay up to date

Properties of all materials vary, as do structural loads such as snow, wind and occupancy. Building design professionals must responsibly deal with this variability in the design process to ensure public safety and protect property. In this article, we focus our discussion on stress-rated dimension lumber. Because no two pieces of lumber are exactly alike, we observe variability in lumber design properties, even after the lumber is sorted into species groupings and grades. Standards and statistical methods are used to derive lumber design values. The updating of published lumber design values is a timely topic and our goal is to help readers understand some of the key issues about variability and the management of variability through grading methods.

Lumber grading systems

In the United States and Canada, softwood lumber is manufactured according to American Softwood Lumber Standard PS 20 (www.alsc.org). The American Lumber Standard Committee, which is comprised of manufacturers, distributors, users and consumers of lumber, updates and administers PS 20 as well as an accreditation program for the grade marking of lumber produced under the system. The American Lumber Standard system provides the basis for acceptance of lumber and design values for lumber by the building codes throughout the United States.

Stress-rated dimension lumber is either visually graded or machine graded. Visual stress rating (VSR) has a long history, with grades such as Select Structural, No. 1, No. 2, No. 3 and Stud. With VSR, a trained lumber grader inspects each piece for characteristics such as knot size and location, slope of grain, checks and wane and then assigns a grade. Prior to grading, the lumber is separated into species groupings such as Southern pine, Douglas fir-larch, and spruce-pine-fir. The groupings are intended to combine species that have similar mechanical properties.

Products currently included in machine-graded lumber are machine stress rated (MSR) lumber and machine evaluated lumber (MEL). Machine grading involves a nondestructive measurement of each piece of lumber, followed by visual inspection by trained lumber graders. Machine-graded lumber generally exhibits less variability in mechanical properties because of the added information provided by the nondestructive measurement of properties correlated to lumber stiffness and strength.

Safety factors

One way to handle variability in lumber strength would be simply to calculate the mean of a representative sample and then divide by a safety factor. Table 1 gives some formulas for calculating common statistics.

Table 1.
Common statistical formulas

Mean	$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n}$
Standard Deviation	$s = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}}$
Coefficient of Variation	$COV = \left(\frac{std\ dev}{mean}\right)$
5th Percentile	$X_{5\%} = \bar{X} - 1.645 \cdot s$

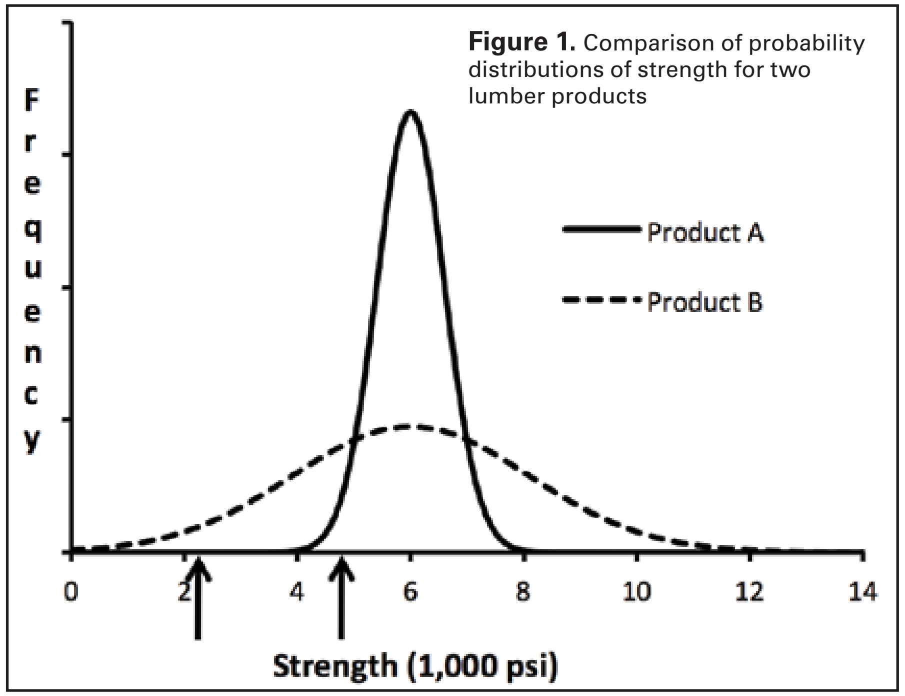

Figure 1. Comparison of probability distributions of strength for two lumber products

Equation 1

$$\text{Allowable Design Value} = \frac{\text{Mean Strength}}{\text{Safety Factor}}$$

An example will illustrate the problem of using this simplistic approach. Suppose we had two lumber products, A and B. Product A is manufactured and graded to have more consistent strength when compared to Product B. Figure 1 shows that even though both products have the same mean or average, the respective variability about the mean is substantially different. Because their means are equal, the use of Equation 1 would result in both products having the same design value. However, examination of the frequency of low strength values for each case clearly shows that the reliability associated with each is not equal and thus, it can be concluded that mean property alone is not sufficient for assigning lumber design values.

Lower 5th percentile approach to design values

The characteristic value used for solid-sawn lumber and many other engineered wood products is the 5th percentile. This is the value that we would expect 5 percent of the strengths to fall below, and 95 percent to fall above. The arrows on Figure 1 show the 5th percentiles for Products A and B. Hence, we start with a "characteristic value" from the lower tail of the probability distribution and then adjust for safety and load duration.

By basing design values on the 5th percentile instead of the mean, we can achieve design values with a more consistent safety level. By basing design values on the lower tail of the distribution, Product A (with more consistent properties) is awarded a higher allowable design value than Product B.

Design values for allowable bending strength (F_b), tensile strength (F_t), shear strength (F_v) and compression strength parallel-to-grain (F_c) are all based on lower-tail 5th percentiles of their respective distributions.

Post-1991 and current approaches for lumber design values

The In-Grade Testing Program was an extensive undertaking in the 1980s to test representative samples of full-sized, visually graded lumber following the procedures of ASTM D1990 and D2915 (ASTM 2012a, 2012b). The In-Grade Testing Program was a massive research project with more than 70,000 specimens, totaling more than one million board feet of lumber, tested in a 10-year period. The in-grade lumber design values were first published in the 1991 National Design Specification Supplement.

Procedures for sampling, testing, data analysis and design-value derivation from in-grade tests are given in ASTM D1990. Details of the process are complicated; they are available in U.S. Department of Agriculture Forest Products Laboratory Report GTR-126 (Evans et al., 2001).

Lumber properties vary between species, grades and sizes, but also within growing regions. Therefore, obtaining samples that are *representative* of the entire growing region is key. It is also important to have *sufficiently large samples* so that 5th percentile values can be computed with confidence. ASTM D1990 and D2915 give guidance on sampling lumber specimens for testing and establishing design values. For example, minimum cell sizes for testing (only one size and grade) were approximately 360.

ASTM D1990 also establishes the importance of correctly estimating the 5th percentiles from data. Lumber properties data rarely follow the normal distribution (symmetric bell shape) shown in Figure 1. To illustrate this point, some typical probability distribution shapes from actual data are shown in Figures 2 and 3. (Non-normal probability distributions commonly used for lumber and wood products are discussed in Suddarth & Bender, 2011.)

Statistical techniques must be used to determine the best-fitting distribution and then calculate the 5th percentile. To make matters even more complicated, a *tolerance limit* is calculated to account for uncertainty in the 5th percentile estimate. Considerable statistical expertise is required to derive allowable design values using ASTM D1990 methodology. The bottom line is that design values have been based on tests of "actual lumber" since 1991. Prior to 1991, design values were based on tests of small clear (2x2) wood specimens chosen to be defect free (perfectly straight grain with no knots or other imperfections).

As an example, the F_b for visually

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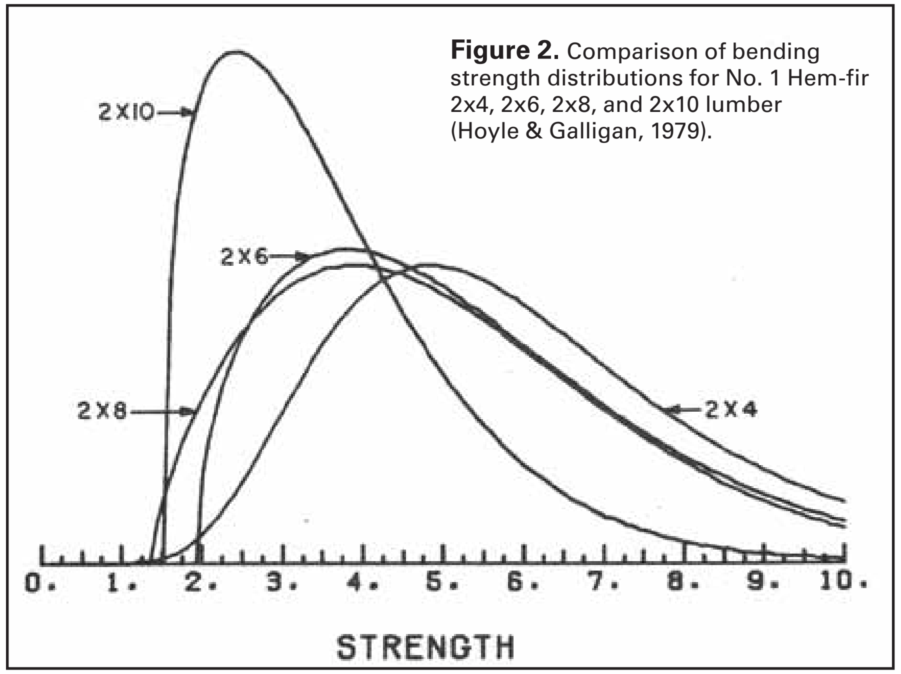

Figure 2. Comparison of bending strength distributions for No. 1 Hem-fir 2x4, 2x6, 2x8, and 2x10 lumber (Hoyle & Galligan, 1979).

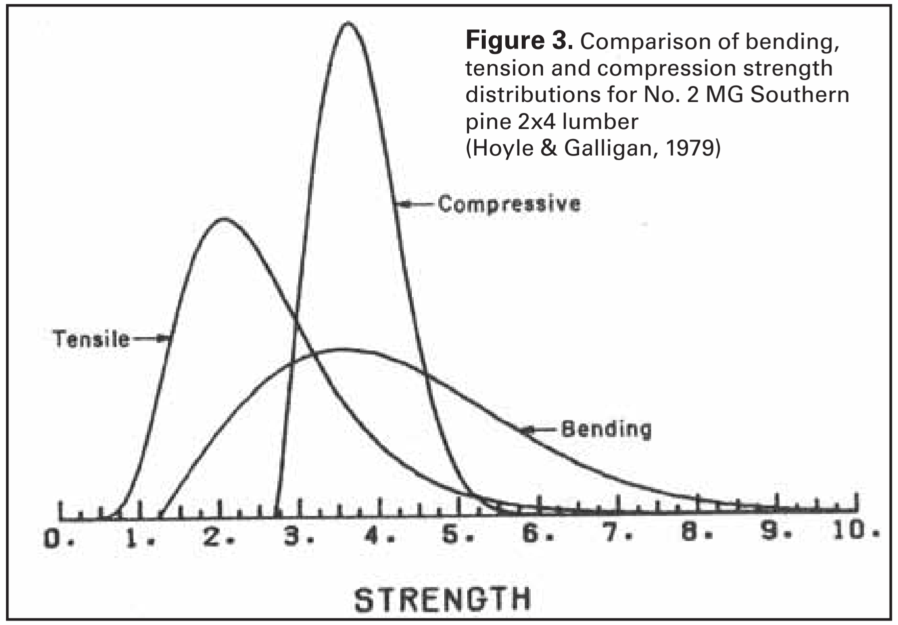

Figure 3. Comparison of bending, tension and compression strength distributions for No. 2 MG Southern pine 2x4 lumber (Hoyle & Galligan, 1979)

graded dimension lumber is tabulated in the NDS (from 1991 to present) as follows (American Wood Council, 2012a):

Equation 2

$F_b = f_{b5\%} * 1/GF$

where $f_{b5\%}$ = lumber bending strength at 5th percentile

GF = general adjustment factor (safety factor and load duration)

The general adjustment factor from ASTM D1990 equals 2.1 and it is the product of a 1.3 safety factor and a 1.6 load duration adjustment. The 1.6 factor adjusts a 10-minute test value to a reference 10-year design value. The safety factor, equal to 1.3, accounts for uncertainty, as is the purpose of design safety factors. It is instructive to note that the historic safety factor of 1.3 on bending and tensile strength does not appear to be excessive and undermines a common myth among some design professionals that published lumber values are overly conservative.

Global design value versus mill-specific value

To understand the difference between a *global design value* and a *mill-specific value,* it is helpful to consider a purely hypothetical and demonstrative example of a representative sample of mills for an entire growth region. Imagine a week of production of five sawmills that are manufacturing a VSR 2x4 grade with F_b equal to 1,650 psi. If you purchased and tested several thousand pieces from each of the five mills, you would obtain a range of test results for the five mills as depicted in Figure 4. Based on the hypothetical situation depicted, one mill, by chance only, produced lumber for the specific week that exactly matched the published value for the size and grade. Two mills produced lumber that had a mill-specific value less than the global design value and two mills produced lumber that had a mill-specific value greater than the global design value.

Because of differences in forests due to factors such as management practices, climate, soils, species mix within a species grouping and log processing variables, the strength of the material from different sawmills will vary from mill to mill and from week to week. This type of variation has been recognized as a natural part of the visual grading system since it was developed nearly a century ago.

The hypothetical global design value of 1,650 psi is used to represent *all* the mills in the growth region for the species or species grouping. A global design value can be thought of as a *weighted result* of all weekly mill-specific values for all mills and weeks throughout the yearly lumber production. Mill-specific values have never been published for lumber produced by the visual grading system. It is not practical or economical for individual mills to conduct the daily destructive tests of their VSR lumber necessary to maintain a mill-specific design value.

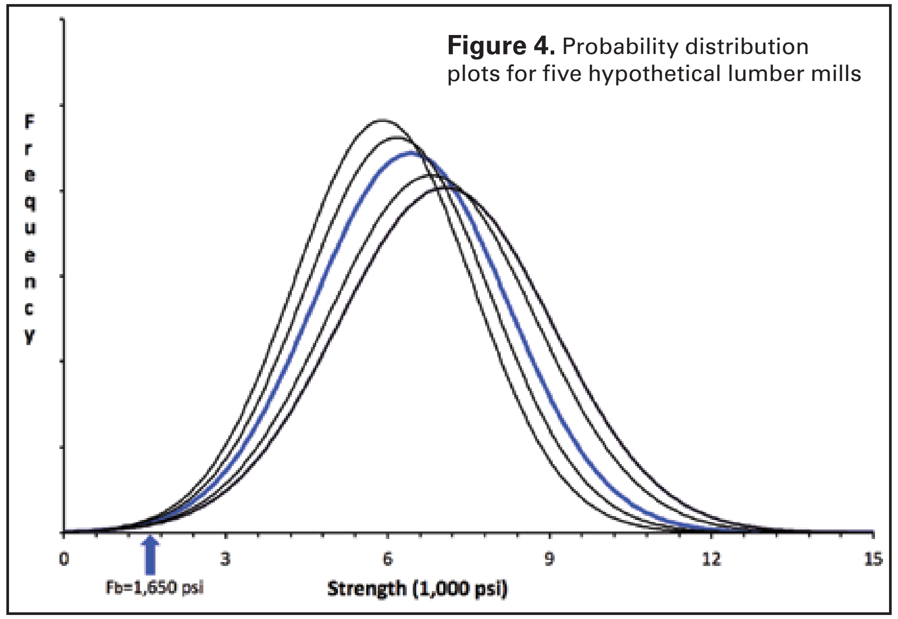

Figure 4. Probability distribution plots for five hypothetical lumber mills

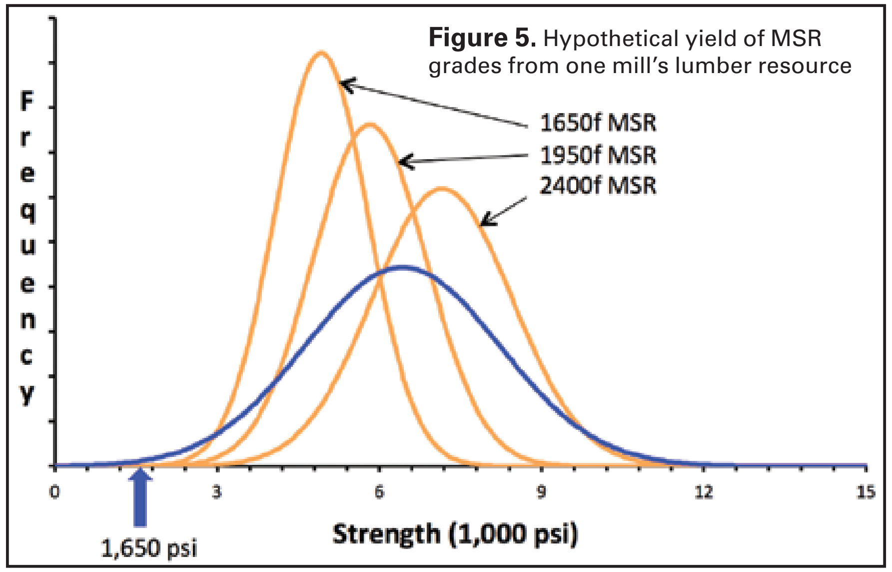

Figure 5. Hypothetical yield of MSR grades from one mill's lumber resource

MSR and MEL design values are mill specific

Assume that the hypothetical VSR lumber mill, timber resource and weekly production represented by the blue line in Figure 4 had been operated as an MSR mill during the same production period. Figure 5 depicts how the same material might be processed in an MSR plant to produce three different grades of MSR. Instead of yielding only lumber with the allowable bending value of 1,650 psi, the same lumber would be efficiently "sorted" by the MSR processing method to yield a variable amount of 1,650f, 1,950f, and 2,400f lumber. For simplicity, we have omitted the "E" designation used to describe an MSR grade.

The technology and grading rules for MSR and MEL differ, as do the quality and testing requirements of the supervisory grading agency (e.g., West Coast Lumber Inspection Bureau, Western Wood Products Association, National Lumber Grades Authority, and Southern Pine Inspection Bureau) for a specific mill. Realizing each agency that supervises MSR and MEL mills has similar methods to produce mechanically graded lumber, we will summarize the MSR process and physical testing aspects of a typical MSR mill.

Overview of VSR and MSR production

Traditional visual stress grading (used to produce VSR lumber) is based on measurements of species, size and grade performance that are determined by sampling the entire range of the growth or production region. The appraisal is not designed to be mill specific. Standard grade rules are applied (e.g., knot size, slope of grain) to segregate the lumber. Frequent (monthly) visual quality appraisals are carried out by sampling inspection in each production facility; the samples are graded at that site to ensure that the selections made meet all aspects of the visual appraisal (the visual grade such as No. 1 or No. 2). As deemed necessary by the supervisory agencies (e.g., the ones listed above), the broad "global" appraisal of the grading system for a specific species (grouping, sizes, grades) is repeated at infrequent intervals. This system has proven to be adequate for traditional wood-frame construction for nearly a century, where elements share loads through repetitive member systems (see NDS Supplement, 2012b, Tables 4A and 4B, for VSR lumber design values).

Machine grading systems combine visual appraisal with nondestructive measurements to produce MSR lumber and MEL. Several significant differences exist between the quality processes for machine grading systems and those of visual grading. This first is that each grade, size or species group to be produced must be specifically appraised for strength and stiffness in each production mill before production can begin. Thus the basis of the system or the establishment of the visual and mechanical criteria for grading of each species, size or grade is mill specific. With the mill-specific criteria established, the second important difference is the requirement for daily sampling (or short-frequency sampling, depending on production) and mechanical testing of the MSR grades produced. Thus variations in the timber resource will be detected and will affect lumber grade and yield as it is being produced; the stability and accuracy of the grading process are regularly appraised by both the visual and the mechanical testing of samples from the production. Manufacturers of engineered structural products such as trusses, I-joists and glued-laminated beams have used lumber from machine graded systems for almost 50 years (see NDS Supplement, 2012b, Table 4C, for MSR and MEL design values).

Summary and conclusions

Visual versus machine lumber grading systems have a basis established in accordance with national standard procedures. Both grading systems segregate and apply quality monitoring to provide design values based on established criteria with the critical differences being (1) mill-specific values for machine graded lumber versus global values for visually graded lumber and (2) periodic quality control based on visual lumber characteristics only (VSR lumber) versus the requirement for daily quality control mechanical testing (MSR lumber and MEL).

Some VSR lumber design values are currently being updated through sampling from representative mills and destructive testing. For example, limited size and grade results are available for Southern pine and mixed Southern pine (www.spib.org/pdfs/Supplement-No-9-Tables-2002-sml-2x4-only.pdf). It is important for the building designer, registered design professional and contractor to be aware of changes in allowable design values that may occur for different species groups of lumber. It should be noted that wood truss, roof purlin, wall girt, door header designs and other wood framing can be affected by updated lumber design values. ***FBN***

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