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 mechanically tested properties than visually graded lumber. Machine-graded lumber following the procedures of ASTM D1990 and D2915 gives some formulas for calculating common statistics.

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>( \bar{x} )</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>( s )</td>
</tr>
<tr>
<td>Standard error of the mean</td>
<td>( \frac{s}{\sqrt{n}} )</td>
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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 proper design values are 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 proper ties) is awarded a higher allowable design value than Product B.

Design values for allowable bending stress (Fb), tensile strength (Ft), shear stress (Fv) and compression strength parallel-to-grain (Fp) 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 at hundreds of locations. 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 percentile value. 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 distribution shapes for solid-sawn lumber are discussed in Suddard & Bender, 2011.)

Statistical techniques must be used to determine the best-fitting distribution and then calculate the 5th percentile. To do so, a tolerance limit or “characteristic value” 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 rated lumber products is 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 stress (\( F_b \)), tensile strength (\( F_t \)), shear stress (\( F_v \)) and compression strength parallel-to-grain (\( F_p \)) are all based on lower-tail 5th percentiles of their respective distributions.

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As an example, the \( F_b \) for visually
graded dimension lumber is tabulated in the NDS (from 1991 to present) as follows (American Wood Council, 2012a):

Equation 2

\[ F_b = \frac{f_{b5\%}}{GF} \]

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 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 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).

Figure 4. Probability distribution plots for five hypothetical lumber mills.


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