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| **Prepared by:** | Ron Anthony and Tom Nehil, P.E. | |
| **Title:** | Determining Allowable Design Stresses for Timber using ASTM Standards D2555 and D245 | |

## Introduction

Timber frame engineers are often faced with the task of determining allowable design stresses (reference design values) for timber species not included in the *National Design Specification for Wood Construction (*NDS©). For many of these species, strength testing has been performed and documented and a standardized procedure exists for establishing allowable properties from the tabulated strength values. American Society for Testing and Materials (ASTM) Standards D2555, *Standard Practice for Establishing Clear Wood Strength Values,* and D245, *Standard Practice for Establishing Structural Grades and Allowable Properties for Visually Graded Lumber*, provide the test data and the code-referenced method for determining allowable design stresses. ASTM D245 also provides the means to adjust the reference design values listed in the NDS© for timbers when the grade-limiting defects are less than permitted by grading rules for Select Structural. This can be beneficial when evaluating load capacity of high-quality timbers in new construction and existing structures. This bulletin summarizes the content of ASTM D2555 and D245 and explains how to interpret them to determine allowable design values. Example calculations are provided to illustrate their use.

To fully understand the scope of ASTM D2555 and D245, and to put this bulletin to use, the reader will need to obtain copies of these ASTM standards. Selected information from the standards has been provided here (with permission of ASTM) so that this bulletin can be read without those documents in hand.

## Rationale for using ASTM D2555 and D245

The NDS© Supplement lists reference design values for lumber and timber for numerous commercial softwood and hardwood species. Table 4D provides the reference design values specific to timbers, that is solid members with a cross section greater than or equal to 5 inches by 5 inches. Species listed are those that are considered to be commercially available. However, historically a wide range of tree species were harvested for use as structural timber that are not found in the NDS Supplement, for example ashes, elms, aspens, basswood, hackberry, honey locust, sycamore and more. Many small mills today have access to and are willing to produce timbers from these non-commercial species. To assess the load-carrying capacity of these species, the designer has need of reference design values that can meet the requirements of the building code. Most North American tree species from which timber can be harvested have been tested to obtain strength properties that are summarized in ASTM D2555. Strength test results are also provided in the *Wood Handbook* produced by the U.S. Department of Agriculture Forest Products Laboratory (available as a free download from https://www.fpl.fs.fed.us). The list of species in the *Wood Handbook* contains all the species in D2555 plus several more that are of interest to timber framers. Differences between the data published in the two publications are discussed below.

Rather than listing individual species, most often the reference design values given in the NDS© Supplement are for species combinations, such as Spruce-Pine-Fir or Mixed Oak. This is an expedient means of addressing the issue that many species are harvested and milled together without sorting by species, and that the species within the group generally have similar mechanical properties. For each of these combinations, there are usually one or two species that are somewhat weaker than the others, and it is the mechanical properties of these species that tend to dictate the reference design values for the group. This is the case for example in the White Oak species combination, which includes white oak, burr oak, chestnut oak, live oak, overcup oak, post oak, swamp chestnut oak, and swamp white oak – a mix of species from the northeast and southeast regions of the U.S. The lower strength properties of burr oak reduces the design values for the group and penalizes the much higher-strength live oak. Similarly, the Mixed Maple combination includes both hard and soft maples, with allowable values being strongly influenced by the mechanical properties of the lower-strength soft maples.

ASTM D2555 provides clear wood strength values for each species for which testing has been performed. Determining allowable design stresses for a particular wood species free from the influence of weaker species that may be in the species group listed in the NDS can be achieved using the test results listed in D2555. For example, if sugar maple (*Acer saccharum)* or white oak

(*Quercus alba)* are the species of interest, then it is possible to develop "unblended" allowable design stresses for those individual species.

Data given in ASTM D2555 were obtained by testing unseasoned small clear specimens (e.g., bending tests were conducted on 2-inch by 2-inch by 30-inch specimens), and do not give allowable design values for seasoned timber with "natural growth characteristics". To obtain reference design values (similar to those published in the NDS), the procedures of ASTM D245 are used. These two ASTM standards together make it possible to derive allowable stresses for most North American timber species.

There is another potential advantage to be gained from using the methods of D245 to derive allowable stresses: the capability to establish allowable properties for a particular combination of natural growth characteristics (strength-reducing features) in a given timber. That is, it provides the means to establish allowable design values for timbers that may have smaller defects than those permitted in the standard grades. Limits to knot size, slope of grain, and other strength-reducing characteristics that are listed in the grading rules approximate Select Structural being assigned a strength 65 percent that of clear wood strength, with No. 1 and No. 2 being 55 percent and 45 percent of clear wood strength, respectively. Put another way, Select Structural has knots, and surprisingly large ones at that. If timbers used in a project contain strength-reducing features that are smaller than the maximum permitted for Select Structural grade, it is possible to "upgrade" the allowable design stresses above those listed in the NDS© Supplement. This option may have some practical use in new construction, and it certainly is beneficial when evaluating the capacity of existing structures and reclaimed timbers where materials may have smaller defects than allowed in Select Structural today.

## ASTM D2555 *Standard Practice for Establishing Clear Wood Strength Values*

ASTM D2555 addresses standard practice for establishing clear wood strength values, and in fact there are several available methods. For purpose of this Technical Bulletin, the relevant part of the standard is the set of tables with strength values that have been obtained for nearly 100 North American hardwood and softwood species. These values were the result of testing conducted in accordance with procedures defined in ASTM D143, *Test Methods for Small Clear Specimens of Timber*.

Figure 1 lists the values tabulated in D2555 for *Quercus alba*, showing the average (mean) and standard deviation values for modulus of rupture (bending strength), shear parallel to grain, compression parallel to grain, and so on. The standard deviation is an indication of the variability of the particular strength property for a given species. The tables in the *Wood Handbook* do not provide the standard deviation; however, the variation is needed when determining allowable design values per D245. Estimates for standard deviation can be developed using assumed variation in accordance with D2555, as discussed in the discussion on the 5% exclusion limit below.

Remember these are strength values and standard deviations for clear wood specimens and so the variability is independent of structural grade; rather it is an indication of the variability of genetic makeup and growth environments of the trees within a species that has been subjected to D143 testing, rather than indicating the strength properties of full-size lumber and timber that include natural-growth characteristics. ASTM D245 procedures take clear wood specimen variability into account when establishing properties that are then used to determine allowable design stresses.

**Figure 1 – Clear Wood Strength Data Provided in ASTM D2555 for White Oak, *Quercus alba*, Unadjusted and in the Unseasoned Condition**

| Property | Average Value, psi | Standard Deviation, psi |
|---|---|---|
| Modulus of Rupture (MOR) | 8300 | 1328 |
| Modulus of Elasticity (MOE) | $1246 \times 10^3$ | $274 \times 10^3$ |
| Compression Parallel to Grain (Crushing Strength) | 3560 | 641 |
| Shear Strength | 1249 | 175 |
| Compression Perpendicular to Grain (Stress at 0.04 in.) | 1109 | |
| Specific Gravity | 0.60 | 0.060 |

## ASTM D245 *Standard Practice for Establishing Structural Grades and Allowable Properties for Visually Graded Lumber*

Despite the title of the standard, D245 does not establish grades in the sense of the grades defined by the lumber rules-writing agencies, such as Western Wood Products Association (WWPA), but rather provides a means of accounting for the maximum defects permitted within a structural grade and determining the related allowable properties for design. Grading rules and the definition of commercial grades are left to the American Lumber Standards Committee (ALSC) and the rules-writing agencies. Structural grades (or stress grades) are defined primarily by characteristics that affect the mechanical properties rather than appearance, although all rules-writing agencies incorporate characteristics that relate to both strength and appearance when establishing grades.

ASTM D245 defines the procedure for determining allowable design stresses for visually graded timbers starting from the average breaking strength values given in D2555 for small clear specimens. These procedures help make the translation from small (2-inch by 2-inch by 30-inch) clear wood specimens to full-size lumber and timbers containing knots and/or slope of grain characteristics. The procedure is a multi-step process that considers the variability of material properties within a given species, adjusts for load duration, incorporates a safety factor, accounts for the effect of slope of grain and knots, when present, and provides other adjustments primarily for size and moisture content.

Using the D143 test data given in D2555, the D245 procedure for establishing allowable properties consists of four basic steps:

i. Calculate the 5% exclusion limit (the lower fifth percentile) for bending, tension parallel to grain, compression parallel to grain, and shear parallel to grain strength properties; note that compression perpendicular to grain and modulus of elasticity are based on average values so the 5% exclusion limit is not applied;
ii. Apply the appropriate adjustment factor for the given clear wood property to achieve a factor of safety and adjust the test data to normal load duration;
iii. Determine the most severe strength ratios to be applied to bending, and tension and compression parallel to grain, to account for the effect of slope of grain and knots. A separate strength ratio is applied to shear parallel to grain to account for checks and splits that may occur;
iv. Determine if any other modification factors apply for the given timber in its anticipated use.

Each of these steps is discussed in more detail below.

- *5% Exclusion Limit:* It is important to understand that the allowable design stresses derived from using D245 procedures are meant to be near-minimum for strength, meaning there is a very low probability that any given piece of lumber or timber will have strength properties below the strength used to calculate allowable design stresses. When a sample set of apparently identical small clear specimens are tested following the procedures of ASTM D143 for a given species, a wide range of strength values are obtained. The results are assumed to reasonably fit a normal distribution curve, so that taking 1.645 times the standard deviation and subtracting that from the average (mean) strength value yields the value below which only five out of 100 test results should fall. This is the 5% exclusion value against which all additional adjustments are made when calculating allowable stresses. Referring to the modulus of rupture values given for white oak in

Table 1, this means that the average bending strength is knocked down by about 25 percent to 6115 psi to establish the 5% exclusion limit for that species, and most species have similar ratios. It also means that approximately half of the pieces tested would have strengths above the mean; for white oak, bending strengths can approach 11,000 psi, roughly 80 percent greater than the 5% exclusion limit! This helps to explain why structural analysis shows material to be deficient in existing structures, yet there is no sign of distress. In fact, the members are not overloaded as the analysis might indicate when based on reference design values from the NDS. This "hidden capacity" of the majority of the material accounts for the high level of performance of many timber structures. Unfortunately, there is no easy means to determine the strength of an individual timber, i.e., where in the strength distribution that piece may be.

When working with a species listed in the *Wood Handbook* but not ASTM D2555, black locust for example, one needs an estimate of the standard deviation for the various properties to calculate the 5% exclusion limits. Fortunately, there is some consistency in the ratio of standard deviation to average strength among the species covered in D2555. The ratios applied to most species are 16 percent for modulus of rupture, 18 percent for compression parallel to grain, and 14 percent for shear parallel to grain. Again, with the 5% exclusion limit taken as average strength minus 1.645 times the standard deviation, this means that the 5% exclusion limits can be estimated at 74 percent, 70 percent and 77 percent of the average strength values respectively for MOR, compression parallel and shear parallel to grain.

- *Adjustment Factors:* Although greatly reduced from the average strengths, the 5% exclusion limits still represent breaking strengths that require further reduction to arrive at allowable design values. Also, the D143 tests are conducted with an expected time-to-failure of 10 minutes. These test results must be modified to adjust the strength value obtained from a 10-minute load duration to allowable stresses suitable for normal load duration, defined as 10 years. Adjustment factors are given in Table 8 of D245 for bending, tension and compression parallel to grain, and horizontal shear. Table 8 is reproduced in Figure 2 below. It also provides adjustment factors for modulus of elasticity and compression perpendicular to grain. The table further differentiates between softwoods and hardwoods for each of the adjustment factors, although the differences are minor. Dividing the 5% exclusion limit value by the appropriate adjustment factor produces the respective allowable properties for clear, straight-grained wood in the unseasoned (green) condition. However, timber framers do not build with small clear wood specimens, so further adjustments are required.

**Figure 2 – Adjustment Factors from ASTM D245**

**TABLE 8 Adjustment Factors to Be Applied to the Clear Wood Properties**

| | Bending Strength | Modulus of Elasticity in Bending | Tensile Strength Parallel to Grain | Compressive Strength Parallel to Grain | Horizontal Shear Strength | Proportional Limit and Stress at Deformation in Compression Perpendicular to Grain |
|---|---|---|---|---|---|---|
| Softwoods | 2.1 | 0.94 | 2.1 | 1.9 | 2.1 | 1.67 |
| Hardwoods | 2.3 | 0.94 | 2.3 | 2.1 | 2.3 | 1.67 |

- *Strength Ratios:* D245 provides a number of strength ratios (reduction factors) to account for the naturally occurring "defects" that may be present in full-size timbers. These defects include knots, slope of grain, checks, splits and shakes.

Wood exhibits the highest strength when loaded parallel to the grain, as opposed to perpendicular to the grain. Compression perpendicular to grain strength is lower than compression parallel strength, but is not affected significantly by the presence of knots, slope of grain, checks or splits and exhibits a ductile failure mode. However, tension perpendicular to grain is not only weaker than tension parallel to grain, it also exhibits a brittle failure mode. Bending stresses applied at an angle to the grain result in tension perpendicular to grain stresses. Compression at an angle results in shear parallel to grain stresses, another weaker and, typically, brittle property. Both of these conditions develop in bending and compression members when the grain is not parallel to the long axis of the stick. This occurs in timber sawn at an angle from the long axis of the log, where the butt log swells at the base of a tree or when timber is sawn from a crooked or twisted stem, or as it occurs around knots.

Strength reductions are severe with even mild grain deviations; when the slope of grain reaches 1 in 6, approximately half of the strength in bending, tension and compression parallel to grain compared is lost compared to a straight-grained stick. A 1 in 6 slope (designated 1:6) corresponds with the maximum permitted for No. 2 grade. D245 provides the strength reduction factors for various slopes of grain from 1:20 to 1:6 for bending and compression members, reproduced in Figure 3 below.

**Figure 3 – Strength Ratios for Slopes of Grain from ASTM D245**

**TABLE 1 Strength Ratios Corresponding to Various Slopes of Grain**

| Slope of Grain | Maximum Strength Ratio, % | |
|---|---|---|
| | Bending or Tension Parallel to Grain | Compression Parallel to Grain |
| 1 in 6 | 40 | 56 |
| 1 in 8 | 53 | 66 |
| 1 in 10 | 61 | 74 |
| 1 in 12 | 69 | 82 |
| 1 in 14 | 74 | 87 |
| 1 in 15 | 76 | 100 |
| 1 in 16 | 80 | ... |
| 1 in 18 | 85 | ... |
| 1 in 20 | 100 | ... |

Knots themselves in timber are not the cause of failure. Failure is initiated in the grain deviations around the knot, where tension perpendicular to grain and shear parallel to grain stresses develop under load. However, strength ratios associated with knots in bending members are derived by comparing the assumed capacity of the member cross section reduced by the area occupied by the knot against that of a same-size member with full cross section. A similar logic is applied to developing strength ratios for compression members with various size knots. It is not an exact science since simplifying assumptions that don't actually correspond with the mechanism of failure are made to predict the effect various knot sizes and locations may have on bending and axial strength of the member. However, testing of full-size lumber has shown empirically that the effect of knots on strength is reasonably accounted for using the procedures of D245.

There are three tables provided in D245 that give the strength ratios for various combinations of knot size and member size. The tables give the strength reducing ratios for knots on the narrow face of bending members, centerline knots on the wide face of members, and edge knots on the wide face of members. For example, a 3-inch knot in the center of the wide face of an 8-inch x 8-inch beam, from Table 3 of D245 (a portion of which is reproduced in Figure 4), gives a strength ratio of 65 percent to be applied to the adjusted clear wood properties. That same size knot in a 16-inch deep timber has less strength-reducing effect and, therefore, as given in the table, a strength ratio of 79 percent should be applied to the adjusted clear wood properties in that case. If that 3-inch knot occurred at the edge of the wide face however, the strength ratios are given in Table 4 of D245 (Figure 5 below) and would be 40 and 62 percent respectively. Similar to the effect of a notch on the tension face of a joist or beam, an edge knot results in a significant loss of strength.

Since actual timbers seldom show these idealized locations for knots, and may have multiple knots in close proximity, there is a system for making the translation from actual knot(s) size and location to these idealized ones based on the concept of equivalent displacement. That approach forms part of the visual grading process, which is beyond the scope of this Bulletin. For more information on this, refer to the Appendix of D245 or grading rules published by any of the rules-writing agencies.

Strength ratios associated with splits, checks and shakes apply only to shear parallel to grain. A strength ratio of 50 percent is used for all sizes of these defects since D245 takes that to be the maximum effect they can have on the load-carrying capacity of a member.

**Figure 4 – Strength Ratios for Centerline Knots from ASTM D245 (partial copy)**

**TABLE 3 Strength Ratios Corresponding to Centerline Knots in the Wide Face of Bending Members, and to Knots in Compression Members**

| Size of Knot, in. (mm)[A] | Percentage Strength Ratio When Actual Width of Wide Face, in. (mm), is[A] | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3 (76) | 3½ (89) | 4 (102) | 4½ (114) | 5 (127) | 5½ (140) | 6 (152) | 7 (178) | 7½ (190) | 8 (203) | 9 (229) | 9½ (241) | 10 (254) | 11 (279) | 11½ (292) | 12 (302) | 13 (330) | 13½ (343) | 14 (356) | 15 (381) | 15½ (394) | 16 (406) | 18 (457) | 20 (508) |
| ¼ (6) | 94 | 95 | 95 | 96 | 96 | 96 | 97 | 97 | 97 | 97 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 98 | 99 | 99 | 99 |
| ½ (13) | 86 | 88 | 90 | 91 | 91 | 92 | 93 | 94 | 94 | 95 | 95 | 95 | 96 | 96 | 96 | 96 | 96 | 96 | 97 | 97 | 97 | 97 | 97 | 97 |
| ¾ (19) | 79 | 82 | 84 | 85 | 87 | 88 | 89 | 91 | 91 | 92 | 92 | 93 | 93 | 94 | 94 | 94 | 94 | 95 | 95 | 95 | 95 | 95 | 95 | 95 |
| 1 (25) | 72 | 75 | 78 | 80 | 82 | 84 | 85 | 87 | 88 | 89 | 90 | 90 | 91 | 92 | 92 | 92 | 92 | 93 | 93 | 93 | 93 | 93 | 94 | 94 |
| 1¼ (32) | 64 | 69 | 72 | 75 | 78 | 79 | 81 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 90 | 90 | 90 | 91 | 91 | 91 | 91 | 91 | 92 | 92 |
| 1½ (38) | 57 | 62 | 67 | 70 | 73 | 75 | 78 | 81 | 82 | 83 | 85 | 85 | 86 | 87 | 88 | 88 | 89 | 89 | 89 | 89 | 90 | 90 | 90 | 91 |
| 1¾ (44) | 49 | 56 | 61 | 65 | 68 | 71 | 74 | 77 | 79 | 80 | 82 | 83 | 84 | 85 | 86 | 86 | 87 | 87 | 87 | 87 | 88 | 88 | 89 | 89 |
| 2 (51) | 35 | 49 | 55 | 60 | 64 | 67 | 70 | 74 | 76 | 77 | 79 | 80 | 81 | 83 | 84 | 84 | 85 | 85 | 85 | 86 | 86 | 86 | 87 | 88 |
| 2¼ (57) | 26 | 37 | 50 | 55 | 59 | 62 | 66 | 71 | 72 | 73 | 77 | 78 | 79 | 81 | 82 | 82 | 83 | 83 | 83 | 84 | 84 | 84 | 85 | 86 |
| 2½ (64) | 18 | 30 | 39 | 50 | 54 | 58 | 62 | 67 | 69 | 71 | 74 | 75 | 77 | 79 | 80 | 80 | 81 | 81 | 81 | 82 | 82 | 83 | 84 | 84 |
| 2¾ (70) | ... | 23 | 32 | 40 | 50 | 54 | 58 | 64 | 66 | 68 | 71 | 73 | 74 | 76 | 77 | 78 | 79 | 79 | 79 | 80 | 80 | 81 | 82 | 83 |
| 3 (76) | ... | ... | 26 | 34 | 41 | 50 | 54 | 61 | 63 | 65 | 69 | 70 | 72 | 74 | 75 | 76 | 77 | 77 | 78 | 78 | 79 | 79 | 80 | 81 |
| 3¼ (83) | ... | ... | ... | 29 | 36 | 45 | 51 | 57 | 60 | 62 | 66 | 68 | 69 | 72 | 73 | 74 | 75 | 75 | 76 | 76 | 77 | 77 | 78 | 80 |
| 3½ (89) | ... | ... | ... | 23 | 31 | 37 | 47 | 54 | 57 | 59 | 64 | 65 | 67 | 70 | 71 | 72 | 73 | 73 | 74 | 75 | 75 | 75 | 77 | 78 |
| 3¾ (95) | ... | ... | ... | ... | 26 | 32 | 38 | 51 | 54 | 56 | 61 | 63 | 65 | 68 | 69 | 70 | 71 | 71 | 72 | 73 | 73 | 74 | 75 | 76 |
| 4 (102) | ... | ... | ... | ... | 21 | 28 | 34 | 47 | 50 | 53 | 58 | 60 | 62 | 66 | 67 | 68 | 69 | 69 | 70 | 71 | 71 | 72 | 73 | 75 |

- *Other Modification Factors:* Several additional modification factors are identified in D245 that can or should be applied as appropriate to the timber and its conditions of use. These modification factors correspond with the "Adjustment Factors" identified in the NDS©, or put another way, D245 is the source document for the Adjustment Factors found in the NDS©. The modification criteria of D245 include moisture content, size, duration of load, aging, preservative or fire retardant treatment including incising effects, temperature, bearing area for compression perpendicular to grain, and repetitive members, as with closely spaced joists or rafters. The modification factors will be familiar to those that use the NDS© Specification and the Supplement regularly and do not require further comment here, with the exception of size and moisture content adjustments.

**Figure 5 – Strength Ratios for Edge Knots from ASTM D245 (partial copy)**

**TABLE 4 Strength Ratios Corresponding to Edge Knots in the Wide Face of Bending Members**

| Knot Size, in. (mm)[A] | Percentage Strength Ratio When Actual Width of Wide Face, in. (mm), is[A] | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2 (51) | 2½ (64) | 3 (76) | 3½ (89) | 4 (102) | 4½ (114) | 5 (127) | 5½ (140) | 6 (152) | 7 (178) | 7½ (190) | 8 (203) | 9 (229) | 9½ (241) | 10 (254) | 11 (279) | 11½ (292) | 12 (305) | 13 (330) | 13½ (343) | 14 (356) | 15 (381) | 15½ (394) |
| ¼ (6) | 83 | 86 | 88 | 89 | 91 | 91 | 92 | 93 | 94 | 94 | 94 | 95 | 95 | 96 | 96 | 96 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |
| ½ (13) | 65 | 71 | 75 | 78 | 80 | 82 | 84 | 85 | 86 | 88 | 89 | 90 | 90 | 91 | 91 | 92 | 92 | 93 | 93 | 93 | 93 | 93 | 93 |
| ¾ (19) | 49 | 57 | 62 | 67 | 70 | 73 | 75 | 77 | 79 | 82 | 83 | 84 | 86 | 86 | 87 | 88 | 89 | 89 | 89 | 89 | 90 | 90 | 90 |
| 1 (25) | 27 | 38 | 51 | 57 | 61 | 65 | 68 | 70 | 73 | 76 | 77 | 79 | 81 | 82 | 83 | 84 | 85 | 85 | 85 | 86 | 86 | 86 | 87 |
| 1¼ (32) | 16 | 27 | 36 | 47 | 52 | 57 | 60 | 63 | 66 | 71 | 72 | 74 | 76 | 77 | 78 | 80 | 81 | 82 | 82 | 82 | 83 | 83 | 83 |
| 1½ (38) | ... | 17 | 26 | 34 | 40 | 49 | 53 | 57 | 60 | 64 | 67 | 69 | 72 | 73 | 74 | 76 | 77 | 78 | 78 | 79 | 79 | 80 | 80 |
| 1¾ (44) | ... | ... | 19 | 26 | 33 | 38 | 47 | 50 | 54 | 60 | 62 | 64 | 67 | 69 | 70 | 72 | 74 | 75 | 75 | 75 | 76 | 77 | 77 |
| 2 (51) | ... | ... | ... | 19 | 26 | 32 | 37 | 45 | 49 | 55 | 57 | 59 | 63 | 65 | 66 | 69 | 70 | 71 | 72 | 72 | 73 | 73 | 74 |
| 2¼ (57) | ... | ... | ... | ... | 20 | 26 | 31 | 36 | 40 | 50 | 52 | 55 | 59 | 61 | 62 | 65 | 66 | 68 | 68 | 69 | 69 | 70 | 71 |
| 2½ (64) | ... | ... | ... | ... | 15 | 21 | 26 | 31 | 35 | 45 | 48 | 51 | 55 | 57 | 59 | 62 | 63 | 65 | 65 | 66 | 66 | 67 | 68 |
| 2¾ (70) | ... | ... | ... | ... | ... | 16 | 21 | 26 | 30 | 38 | 41 | 46 | 51 | 53 | 55 | 59 | 60 | 61 | 62 | 63 | 63 | 64 | 65 |
| 3 (76) | ... | ... | ... | ... | ... | ... | 17 | 21 | 26 | 33 | 37 | 40 | 47 | 50 | 52 | 55 | 57 | 58 | 59 | 60 | 60 | 61 | 62 |

Regarding size, the reference design value for bending developed in the first three steps are based on test results from a 2-inch depth test specimen. To adjust the bending stress for other depths, a factor is applied, calculated as $F = (\frac{2}{d})^{1/9}$. The bending values in Table 4D of the Supplement have been "registered" to a 12-inch depth, meaning that a factor of $F = (\frac{2}{12})^{1/9} = 0.82$ has been applied. In the notes preceding Table 4D, the size factor $C_F$ is defined. It requires further reduction in the design bending stress only for sizes greater than 12 inches; there is no increase given for smaller dimensions. The size factor does not change drastically with smaller dimension timber, but could be significant. For example, the value of F is 0.88 for a 6-inch deep bending member. When working through the D245 process, the size factor needs to be calculated and applied.

Regarding moisture content, as wood dries below the fiber saturation point, its strength and stiffness increase. Up to this point in the calculation of design values, green lumber has been assumed, that is, lumber at a moisture content presumably at or above the fiber saturation point, assumed to be 30 percent. D245 provides modification factors, reproduced here in Figure 6, to account for the benefits of seasoning down to 19 percent and 15 percent for dimension lumber. Note the increase in bending strength is 25 and 35 percent, respectively, for each of these moisture contents, and the increase in compression parallel is even greater at 50 and 75 percent, respectively. The design values for dimension lumber given in Table 4A of the Supplement are based on a moisture content of 19 percent. For timber (5 inches or greater in thickness), D245 notes that "these increases may be offset to varying extent by the shrinkage and seasoning defects that occur." The factors given in Table 10, as provided and explained, are not intended to be applied to timber, except when loaded in compression.

The reference design values provided in Table 4D of the Supplement depart from ASTM D245 for drying effects on compression stresses. For continuous dry use, a 10 percent increase in compression parallel and a 50 percent increase in compression perp are taken even though the timbers are considered to be in the green condition. Adjustment factors provided for Table 4D include a wet service factor, $C_M$. For wet service conditions, compression perp is to be reduced by 0.67, and compression parallel to grain by 0.91, backing out the seasoning increases of 50 percent and 10 percent respectively that have been applied to these two values. (The exception to this is southern pine, where no seasoning effects have been incorporated and so no adjustment factors need be applied for wet service.) It would seem reasonable to follow industry practice when applying seasoning effects to timber by at least increasing allowable compressive stresses. Whether other properties might be reasonably increased as well is discussed below.

**Figure 6 – Modification Factors for Seasoning Effects from ASTM D245**

**TABLE 10 Modification of Allowable Stresses for Seasoning Effects for Lumber 4 in. and Less in Nominal Thickness (9)[A]**

| Property | Percentage Increase in Allowable Property Above That of Green Lumber When Maximum Moisture Content is | |
|---|---|---|
| | 19 % | 15 % |
| Bending | 25 | 35 |
| Modulus of elasticity | 14 | 20 |
| Tension parallel to grain | 25 | 35 |
| Compression parallel to grain | 50 | 75 |
| Horizontal shear | 8 | 13 |
| Compression perpendicular to grain | 50[A] | 50[A] |

[A]The increase in compression perpendicular to grain is the same for all degrees of seasoning below fiber saturation since the outer fibers which season rapidly have the greatest effect on this strength property regardless of the extent of the seasoning of the inner fibers.

A couple more notes before tackling an example calculation: Table 4D in the Supplement also provides values for $E_{min}$ and specific gravity. The derivation of $E_{min}$, the lower bound modulus of elasticity to be used in beam and column stability calculations in the NDS©, does not form part of ASTM D245, but rather is given in the Commentary to the NDS© in C4.2.4. $E_{min}$ incorporates not only the 5% exclusion limit concept, but also an adjustment factor and a further safety factor. Refer to the NDS Commentary for details.

Additionally, the values for specific gravity given in D2555 represent "basic specific gravity", $G_b$, that is, ovendry weight divided by green volume, while the values in the NDS© Supplement are for $G_0$, ovendry weight divided by ovendry volume. The translation between the two can be made by applying Equation (4-11) from the *Wood Handbook*. This equation is based on an estimate for volumetric shrinkage. When translating from basic specific gravity to ovendry specific gravity, the equation becomes: $G_0 = G_b/(1 - 0.265\, G_b)$ .

## Example Calculation

White, green and black ash have become available as lumber and timber in great quantity due to the infestation of the emerald ash borer. Ash is not one of the species included in the NDS© Supplement so it provides a good example case for using the ASTM D2555 and D245 standards to derive design values.

Strength data for white ash as given in D2555 are shown in Figure 7. For this example, calculation the goal is to establish design values for visually graded timber with depth of 10 inches meeting or exceeding the requirements for No. 1 grade Beams and Stringers (B&S) as defined in the grading rules issued by the Northeast Lumber Manufacturers Association (NeLMA).

In the 2013 edition of the NeLMA rules, the maximum slope of grain permitted for No. 1 grade B&S is 1:10, the maximum size centerline knot on the wide face is 3 ¾ inches, and the maximum edge knot on the wide face is 2 ⅞ inches. No limit is given for knot size on the narrow face of timbers since NeLMA's visual grading procedure considers narrow face knots as equivalent edge or centerline knots. The grading rules identify several other limits, but these three are sufficient for this calculation.

The following then walks through the four steps identified earlier.

i. *Calculate the 5% exclusion limit for bending, compression parallel and shear parallel to grain.* Tension parallel to grain strength is based on a percentage of bending strength in the D245 procedure and does require a separate calculation; it is addressed in step (iii) where strength ratios are calculated.

- Bending strength at 5% exclusion limit: $9500 - (1.645 \times 1520) = 7000$ psi
- Compression parallel to grain at 5% exclusion limit: $3990 - (1.645 \times 718) = 2809$ psi
- Shear parallel to grain at 5% exclusion limit: $1354 - (1.645 \times 190) = 1041$ psi

ii. *Apply the adjustment factors from Table 8 of D245*:

- Bending strength: $7000 \times \frac{1}{2.3} = 3043$ psi
- Modulus of elasticity: $1436 \times \frac{1}{0.94} = 1528 \times 10^3$ psi
- Compression parallel: $2809 \times \frac{1}{2.1} = 1338$ psi

- Horizontal shear strength: $1041 \times \frac{1}{2.3} = 453$ psi
- Compression perpendicular to grain: $1102 \times \frac{1}{1.67} = 660$ psi

**Figure 7 – Strength Data Provided in ASTM D2555 for White Ash, *Fraxinus americana***

| Property | Average Value, psi | Standard Deviation, psi |
|---|---|---|
| Modulus of Rupture (MOR) | 9500 | 1520 |
| Modulus of Elasticity (MOE) | 1436 x $10^3$ | 316 x $10^3$ |
| Compression Parallel to Grain (Crushing Strength) | 3990 | 718 |
| Shear Strength | 1354 | 190 |
| Compression Perpendicular to Grain (Stress at .04 in.) | 1102 | |
| Specific Gravity | 0.54 | 0.054 |

iii. *Determine and apply strength ratios*. For bending strength and compression parallel to grain, we take the worst case from the slope of grain ratio and the centerline and edge knot ratios. From Table 1 of D245, a slope of grain of 1 in 10 requires a strength ratio of 61 percent for bending and 74 percent for compression parallel to grain. For a 3 ¾ inch centerline knot in a 10-inch deep beam, the strength ratio is 65 percent. This ratio applies to both bending and compression members. From Table 4 of D245, for a 2 ⅞-inch edge knot in a 10-inch deep beam the strength ratio is 53 percent (interpolated between 2 ¾ and 3-inch knots). This table applies to bending members only. The knot sizes have a greater impact than slope of grain, so those strength ratios are used. Tension parallel to grain is based on bending strength, as noted earlier, and the strength ratio for this property is 55 percent of the bending strength ratio. For shear parallel to grain, use the strength ratio of 0.50 stipulated by D245. This yields:

- Bending strength: $3043 \times 0.53 = 1613$ psi
- Tension parallel to grain: $3043 \times 0.53 \times 0.55 = 887$ psi
- Compression parallel: $1338 \times 0.65 = 870$ psi
- Horizontal shear strength: $453 \times 0.50 = 227$ psi

Strength of compression perp is not affected by grade so no strength ratios apply. Modulus of elasticity is affected by grade, however, and a "Quality Factor" is used to adjust MOE as a function of the bending strength ratio. The quality factors are given in

Table 5 of D245 (see Figure 6), and for bending strength ratios of 45 to 54 percent, that factor is 90 percent, so:

- Modulus of elasticity: $1528 \times 0.90 = 1375 \times 10^3$ psi

**Figure 6 – Quality Factors for MOE from ASTM D245**

**TABLE 5 Quality Factors for Modulus of Elasticity**

| Bending Strength Ratio, % | Quality Factor for Modulus of Elasticity, % |
|---|---|
| ≥55 | 100 |
| 45 to 54 | 90 |
| ≤44 | 80 |

Looking at the values provided for modulus of elasticity in the NDS© Supplement, Select Structural and No. 1 grades for all species are always identical. MOE is only reduced for No. 2. This is based on the concept within the grading rules to establish strength ratios for Select Structural at 65 percent, No. 1 at 55 percent, and No. 2 at 45 percent. At 55 percent and above strength ratios, Table 5 of D245 indicates the quality factor for MOE is 100 percent. In fact, looking at the specifics for slope of grain and knot sizes in establishing the strength ratio for No. 1 grade might have been skipped and a short cut taken by applying a 55 percent strength ratio for this calculation. However, the strength ratios obtained by working through the procedures of D245 do not exactly follow these simple percentages, and the results can be more favorable.

iv. *Determine and apply other modification factors*. For this calculation it is assumed the timbers will be used in applications protected from weather. As discussed, seasoning effects are incorporated into the NDS© Supplement values for compression parallel and perpendicular to grain when continuously dry service conditions are anticipated and will be applied here as increases of 10 and 50 percent, respectively. Since the design bending stress developed to this point is based on a 2-inch depth, a size factor will apply to the 10-inch deep beams assumed here. That factor is $F = (\frac{2}{d})^{1/9} = (\frac{2}{10})^{1/9} = 0.84$ . Assuming normal load duration, no preservative or other treatment, or incising, and normal temperatures in service, no other factors apply.

D245 indicates that allowable property values are to be rounded off, with bending, tension and compression parallel to grain rounded to the nearest 50 psi when the value is greater than 1000 psi, or 25 psi when less than 1000 psi. Horizontal shear and compression perp are to be rounded to the nearest 5 psi. Modulus of elasticity is rounded to the nearest 100,000 psi.

Applying these final modification factors and then rounding off gives the reference design values for No.1 white ash 10-inch deep beams in dry service conditions:

- Bending: $F_b = 1613 \times 0.84 = 1350$ psi
- Tension parallel to grain: $F_t = 875$ psi
- Shear parallel to grain: $F_v = 225$ psi
- Compression perpendicular to grain: $F_{c\perp} = 660 \times 1.50 = 990$ psi
- Compression parallel to grain: $F_c = 870 \times 1.10 = 950$ psi
- Modulus of Elasticity: $E = 1{,}400{,}000$ psi
- Specific gravity: $G = \frac{0.54}{1-0.265 \times 0.54} = 0.63$

## Timbers of Higher Grade

In the course of designing and building a timber frame structure, situations commonly arise where demand on certain timbers exceeds their capacity as designated by NDS©. Assuming span and loading conditions are given, solutions include changing the size of the timbers, or using a different species or grade. This last option may be practical if higher quality timbers are available. In fact, reference design stresses greater than those for Select Structural can be established and incorporated into a specification when purchasing timbers or examining timbers already purchased. It's just a matter of revisiting the strength ratios of step iii. Note that there is nothing preordained about the grades established by the lumber grading agencies. Select Structural, No.1 and No.2 are just arbitrary lines drawn in the continuum to facilitate "the orderly marketing of lumber" as is stated in D245.

Returning to the example calculation above, if it were found certain timbers exhibited a slope of grain not more than 1 in 16, had centerline knots 1 ½ inch or less, and edge knots no greater than 1 inch, then examining Figures 2, 3 and 4 above, the limiting strength ratio would be 80 percent for bending, controlled by the slope of grain. This would permit increasing the bending stress, tension parallel to grain stress, and modulus of elasticity. The values would increase to 2050 psi, 1300 psi and 1,500,000 psi, respectively. That's a 50 percent bump in allowable bending stresses, which could be enough to address the design challenges encountered by the engineer.

When evaluating fully seasoned timbers in existing structures, there is also an opportunity to determine whether the 50 percent strength ratio for shear parallel is appropriate for a given timber. Should a timber be free from visible splits, checks or shake, then consideration could be given to increasing the allowable shear stress if that were a limiting factor for its intended use.

This grading procedure can be applied to any species or species combination found in the NDS© Supplement.

## Timbers in Existing Structures

The process of establishing design values tailored to the specific characteristics in a given timber, or group of timbers, applies equally well to existing structures. Particularly in historic structures built with old growth southern yellow pine or Douglas-fir, it is common to find large timbers with only small, tight knots. In buildings were such timbers were used, slope of grain often becomes the limiting factor when determining strength ratios. If the quality of timbers in a given building, or of a particular timber that has high demand, are better quality than Select Structural, then use of D245 to establish higher allowable stresses without involving the expense of materials testing or load testing, can reduce or eliminate the expense (and harm) of strengthening and is an option that any structural engineer involved in preservation or adaptive reuse should be aware of.

Whether design values for bending, tension and compression parallel to grain, and horizontal shear might be further increased when timbers visually graded in situ are found to be at low moisture contents, say 12% or less, is the subject of current research and development. Timbers in existing structures that are protected from weather will have undoubtedly reached equilibrium moisture content through their full thickness after a few years of service and it would appear justified to take advantage of the strength increases in the wood that develop with drying. Any increases in design values considered should be applied against the actual measured dimensions of the timber rather than nominal dimensions and the timber should be graded so that any strength-reducing characteristics that have developed as a result of drying are incorporated. Since drying checks typically do not have an effect on bending or axial capacity, the potential increases in allowable stresses could more than compensate for dimensional changes. The incorporation of seasoning effects to increase reference design values for timbers would provide an additional basis for increasing the calculated load-bearing capacity of existing structures when appropriate.

*Ron Anthony* is a wood scientist and is the President of Anthony & Associates, Inc. located in Fort Collins, CO. He is a member of TFEC, a Fellow in the Association of Preservation Technology International, and has served as the Chair of ASCE's Forensic Engineering Division. He is the 2002 recipient of the James Marston Fitch Foundation Grant for his approach to evaluating timber in historic buildings.

*Tom Nehil, P.E.* is Principal Emeritus with Nehil•Sivak Structural Engineers in Kalamazoo, Michigan, and a Past-Chairman of the TFEC where he chairs the Timber Grading Training Committee