Designation: D 5457 – 04a

Standard Specification for Computing Reference Resistance of Wood-Based Materials and Structural Connections for Load and Resistance Factor Design[1]

This standard is issued under the fixed designation D 5457; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Load and resistance factor design (LRFD) is a structural design method that uses concepts from reliability theory and incorporates them into a procedure usable by the design community. The basic design equation requires establishing a reference resistance based on several material property parameters. A standard method for calculating the required material property input data is critical so that all wood-based structural materials can be treated equitably. This specification provides the procedures that are required for the generation of reference resistance for LRFD.

1. Scope

1.1 This specification covers procedures for computing the reference resistance of wood-based materials and structural connections for use in load and resistance factor design (LRFD). The reference resistance derived from this specification applies to the design of structures addressed by the load combinations in ASCE 7-02.

1.2 A commentary to this specification is provided in Appendix X1.

2. Referenced Documents

2.1 *ASTM Standards:* [2]

D 9 Terminology Relating to Wood
D 143 Test Methods for Small Clear Specimens of Timber
D 198 Test Methods of Static Tests of Lumber in Structural Sizes
D 1037 Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials
D 1761 Test Methods for Mechanical Fasteners in Wood
D 1990 Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber From In-Grade Tests of Full-Size Specimens
D 2718 Test Methods for Structural Panels in Planar Shear (Rolling Shear)
D 2719 Test Methods for Structural Panels in Shear Through-the-Thickness
D 2915 Practice for Evaluating Allowable Properties for Grades of Structural Lumber
D 3043 Test Methods for Testing Structural Panels in Flexure
D 3500 Test Methods for Structural Panels in Tension
D 3501 Test Methods for Wood-Based Structural Panels in Compression
D 3737 Practice for Establishing Allowable Properties for Structural Glued Laminated Timber (Glulam)
D 4761 Test Methods for Mechanical Properties of Lumber and Wood-Base Structural Material
D 5055 Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists
D 5456 Specification for Evaluation of Structural Composite Lumber Products
E 105 Practice for Probability Sampling of Materials

2.2 *ASCE Standard:*[3]

ASCE 7-02 Minimum Design Loads for Buildings and Other Structures

3. Terminology

3.1 *Definitions*—For general definitions of terms related to wood, refer to Terminology D 9.

3.1.1 *coefficient of variation,* CV_w—a relative measure of variability. For this specification, the calculation of CV_w is based on the shape parameter of the 2-parameter Weibull distribution. It is not the traditional sample standard deviation of the data divided by the sample mean.

[1] This specification is under the jurisdiction of ASTM Committee D07 on Wood and is the direct responsibility of Subcommittee D07.02 on Lumber and Engineered Wood Products.

Current edition approved Nov. 1, 2004. Published November 2004. Originally approved in 1993. Last previous edition approved in 2004 as D 5457 - 04.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from The American Society of Civil Engineers (ASCE), 1801 Alexander Bell Dr., Reston, VA 20191.

3.1.2 *data confidence factor,* Ω—a factor that is used to adjust member reference resistance for sample variability and sample size.

3.1.3 *distribution percentile,* R_p—the value of the distribution associated with proportion, *p*, of the cumulative distribution function.

3.1.4 *format conversion factor,* K_F—a factor applied to convert resistance from the allowable stress design (ASD) format to the LRFD format.

3.1.5 *lower tail*—a portion of an ordered data set consisting of all test specimens with the lowest property values (for example, lowest strengths).

3.1.6 *reference resistance,* R_n—the value used in LRFD equations to represent member resistance (that is, strength or capacity).

3.1.7 *reliability normalization factor,* K_R—a factor used to establish the reference resistance to achieve a target reliability index for a reference set of conditions.

3.1.8 *resistance factor*—a factor applied to the resistance side of the LRFD equation.

4. Sampling

4.1 Samples selected for analysis and implementation with this specification shall be representative of the population about which inferences are to be made. Both manufacturing and material source variability shall be considered. The principles of Practice E 105 shall be maintained. Practice D 2915 provides methods for establishing a sampling plan. Special attention is directed to sampling procedures in which the variability is low and results can be influenced significantly by manufacturing variables. It is essential that the sampling plan address the relative magnitude of the sources of variability.

4.1.1 Data generated from a quality control program shall be acceptable if the criteria of 4.1 are maintained.

4.1.2 When data from multiple data sets are compiled or grouped, the criteria used to group such data shall be in keeping with the provisions of 4.1. When such procedures are available in applicable product standards, they shall be used.

4.2 *Sample Size*:

4.2.1 For data sets in which all specimens are tested to failure, the minimum sample size shall be 30.

NOTE 1—The confidence with which population properties can be estimated decreases with decreasing sample size. For sample sizes less than 60, extreme care must be taken during sampling to ensure a representative sample.

4.2.2 For lower tail data sets, a minimum of 60 failed observations is required for sample sizes of $n = 600$ or less. (This represents at least the lower 10 % of the distribution.) For sample sizes greater than 600, a minimum of the lowest 10 % of the distribution is required (for example, sample size, $n = 720$, 0.10 (720) = 72 failed test specimens in the lower tail). Only parameter estimation procedures designed specifically for lower tail data sets shall be used (see Appendix X2).

5. Testing

5.1 Testing shall be conducted in accordance with appropriate standard testing procedures. The intent of the testing shall be to develop data that represent the capacity of the product in service.

5.2 *Periodic Property Assessment*—Periodic testing is recommended to verify that the properties of production material remain representative of published properties.

6. Reference Resistance for LRFD

6.1 The derivation of LRFD reference resistance is addressed in this section. Parameters required for the derivation of reference resistance are also presented. These parameters include the distribution percentile, coefficient of variation, data confidence factor, and reliability normalization factor. An example derivation of reference resistance is provided in X1.7.

6.2 *Reference Resistance,* R_n—The following equation establishes reference resistance for LRFD:

$$R_n = R_p \times \Omega \times K_R \quad (1)$$

where:
R_p = distribution percentile estimate,
Ω = data confidence factor, and
K_R = reliability normalization factor.

6.3 *Distribution Percentile Estimate,* R_p:

6.3.1 Eq 2 is intended to be used to calculate any percentile of a two-parameter Weibull distribution. The percentile of interest depends on the property being estimated.

$$R_p = \eta[-ln(1-p)]^{1/\alpha} \quad (2)$$

where:
η = Weibull scale parameter,
p = percentile of interest expressed as a decimal (for example, 0.05), and
α = Weibull shape parameter.

6.3.2 The shape (α) and scale (η) parameters of the two-parameter Weibull distribution shall be established to define the distribution of the material resistance.[4] Algorithms for common estimation procedures are provided in Appendix X2.

6.4 *Coefficient of Variation,* CV_w—The coefficient of variation of the material is necessary when determining the data confidence factor, Ω, and the reliability normalization factor, K_R. The CV_w can be estimated from the shape parameter of the Weibull distribution as follows:

$$CV_w \cong \alpha^{-0.92} \quad (3)$$

NOTE 2—The above approximation is within 1 % of the exact solution for CV_w values between 0.09 and 0.50. An exact relationship of CV_w and α is shown in Appendix X3.

6.5 *Data Confidence Factor,* Ω—The data confidence factor, Ω, accounts for uncertainty associated with data sets.[5] This factor, which is a function of coefficient of variation, sample size, and reference percentile, is applied as a multiplier on the distribution estimate. Table 1 provides data confidence factors appropriate for lower fifth-percentile estimates.

NOTE 3—When a distribution tolerance limit is developed on a basis consistent with Ω, the data confidence factor is taken as unity.

[4] Weibull, W., "A Statistical Theory of the Strength of Materials," *Proceedings of the Royal Swedish Institute of Engineering Research*, Stockholm, Sweden, Report No. 151, 1939, pp. 1–45.

[5] *Load and Resistance Factor Design for Engineered Wood Construction—A Pre-Standard Report*, American Society of Civil Engineers, 1988.

TABLE 1 Data Confidence Factor, Ω on $R_{0.05}$, for Two-Parameter Weibull Distribution with 75 % Confidence[A]

CV_w	Sample Size, n									
	30	40	50	60	100	200	500	1000	2000	5000
0.10	0.95	0.95	0.96	0.96	0.97	0.98	0.99	0.99	0.99	1.0
0.15	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	0.99	0.99
0.20	0.89	0.91	0.92	0.93	0.94	0.96	0.98	0.98	0.99	0.99
0.25	0.87	0.88	0.90	0.91	0.93	0.95	0.97	0.98	0.98	0.99
0.30	0.84	0.86	0.88	0.89	0.92	0.94	0.96	0.97	0.98	0.99
0.35	0.81	0.84	0.86	0.87	0.90	0.93	0.96	0.97	0.98	0.99
0.40	0.79	0.81	0.84	0.85	0.89	0.92	0.95	0.96	0.97	0.98
0.45	0.76	0.79	0.82	0.85	0.87	0.91	0.94	0.96	0.97	0.98
0.50	0.73	0.77	0.80	0.81	0.86	0.90	0.94	0.95	0.97	0.98

[A] Interpolation is permitted. For CV_w values below 0.10, the values for 0.10 shall be used.

TABLE 2 Specified LRFD Resistance Factors, ϕ_s

Application	Property	ϕ_s
Member	compression[A]	0.90
	bending, lateral buckling (stability)	0.85
	tension parallel	0.80
	shear, radial tension	0.75
Connection	all	0.65
Shear Wall, diaphragm	shear	0.80

[A] Compression parallel-to-grain, compression perpendicular-to-grain, and bearing.

6.6 *Reliability Normalization Factor, K_R*—The reliability normalization factor, K_R, is used to adjust the distribution estimate (for example, $R_{0.05}$) to achieve a target reliability index. The reliability normalization factor is the ratio of the computed resistance factor, ϕ_c(X1.7), to the specified resistance factor, ϕ_s(Table 2), adjusted by a scaling factor. This adjustment factor is a function of CV_w and is generated for specific target reliability indices. The K_R values presented in Table 3 represent resistance factors (ϕ_c) computed at a live-to-dead load ratio of 3. Computations for determining reliability normalization factors for target reliability indices greater than β = 2.4 are contained in Zahn.[6]

TABLE 3 Fifth-Percentile Based Reliability Normalization Factors, K_R

CV_w,%	K_R					
	Compression and Bearing	Bending	Tension Parallel	Shear (2.1 basis)	Shear (SCL, 3.15 basis)	Shear (I-Joist, 2.37 basis)
10	1.303	1.248	1.326	1.414	0.943	1.253
11	1.307	1.252	1.330	1.419	0.946	1.257
12	1.308	1.253	1.331	1.420	0.947	1.258
13	1.306	1.251	1.329	1.418	0.945	1.256
14	1.299	1.244	1.322	1.410	0.940	1.249
15	1.289	1.235	1.312	1.400	0.933	1.240
16	1.279	1.225	1.302	1.388	0.926	1.230
17	1.265	1.212	1.288	1.374	0.916	1.217
18	1.252	1.199	1.274	1.359	0.906	1.204
19	1.237	1.185	1.259	1.343	0.895	1.190
20	1.219	1.168	1.241	1.324	0.882	1.173
21	1.204	1.153	1.225	1.307	0.871	1.158
22	1.186	1.136	1.207	1.287	0.858	1.141
23	1.169	1.120	1.190	1.269	0.846	1.125
24	1.152	1.104	1.173	1.251	0.834	1.109
25	1.135	1.087	1.155	1.232	0.821	1.092
26	1.118	1.071	1.138	1.214	0.809	1.076
27	1.105	1.059	1.125	1.200	0.800	1.063
28	1.084	1.038	1.103	1.176	0.784	1.042
29	1.066	1.021	1.085	1.157	0.771	1.025
30	1.049	1.005	1.068	1.139	0.759	1.009

6.7 *Format Conversion*:

6.7.1 As an alternative to the use of K_R, in which one chooses to adjust the design values to achieve a stated reliability index under the reference load conditions, it is permissible to generate LRFD reference resistance values based on format conversion from code-recognized allowable stress design (ASD). It shall not be claimed that reference resistance values generated in this manner achieve a stated reliability index.

NOTE 4—Examples of standards that are used to generate code-recognized ASD values include Test Methods D 143, D 198, D 1037, D 1761, D 2718, D 2719, D 3043, D 3500, D 3501, and D 4761; Practices D 1990 and D 3737; and Specifications D 5055 and D 5456.

6.7.2 For standardization purposes, format conversion reference resistance values shall be based on the arithmetic conversion at a specified reference condition that results from the calibration (defined as providing an identical required section modulus, cross-sectional area, allowable load capacity, and so forth) of basic ASD and LRFD equations. The specified reference condition shall be chosen such that changes in design capacity over the range of expected load cases and load ratios is minimized.

6.7.3 Based on the same load factors and load ratio as those given in 6.6, with an ASD load duration adjustment factor of 1.15 and a LRFD time effect factor of 0.80, the format conversion factor, K_F, is as follows:

$$K_F = \frac{2.16}{\phi_s} \tag{4}$$

6.7.4 Since ASD deformation-based compression perpendicular to grain values are not subject to the duration of load adjustment, the constant in the numerator of Eq 4 is 1.875 for this property.

6.7.5 Since neither ASD nor LRFD modulus of elasticity values are subject to duration of load or time effect adjustments, the constant in the numerator of Eq 4 is 1.5 when modulus of elasticity is used in a strength (rather than stiffness) calculation (such as stability).

6.7.6 Since design capacities for shear walls or diaphragms are based on a set of different reference conditions than those given in 6.6, the constant in the numerator of Eq 4 is 1.6 for these assemblies.

NOTE 5—This revised constant is only intended to be applied to the design capacity of shear wall or diaphragm assemblies–not to the design of individual members or subcomponents of these assemblies. The constant in 6.7.3 is to be used for design of individual members or subcomponents of shear walls or diaphragms.

6.7.7 The format conversion reference resistance is computed by multiplying the ASD resistance (based on normal 10-year duration for members and connections) by K_F.

6.7.7.1 *Exception*—The format conversion reference resistance for shear walls and diaphragms is based on a short-term duration.

[6] Zahn, J., *FORTRAN Programs for Reliability Analysis*, USDA Forest Service, FPL GTR-72, Forest Products Laboratory, Madison, WI, 1992.

6.7.8 *Format Conversion Example*—An ASD bolt design value for a single shear connection is 800 lbf. From Table 2, the specified LRFD resistance factor is 0.65. Using Eq 4, the corresponding LRFD bolt design value is as follows:

$$R_n = \left(\frac{2.16}{0.65}\right) \times 800 \quad (5)$$

$$R_n = 2658 \text{ lbf}$$

6.7.9 *Format Conversion Example for Shear Walls or Diaphragms*—An ASD shear wall design value is 395 lb/ft. From Table 2, the specified LRFD resistance factor is 0.80. Using Eq 4, the corresponding LRFD shear wall design value is as follows:

$$R_n = \left(\frac{1.6}{0.80}\right) \times 395 \quad (6)$$

$$R_n = 790 \text{ lb/ft}$$

7. Presentation of Results

7.1 Report the sampling plan and testing in accordance with applicable standards. When lower tail data sets are used, report the sample size and data used in the calculations. Report the estimated shape and scale parameters along with the calculated coefficient of variation. When appropriate, also report the mean and standard deviation (derived from the calculated coefficient of variation). Include a plot showing the data points and fitted Weibull distribution. In addition to these basic parameters, also report the data confidence factor, calculated percentile estimate, reliability normalization factor, and reference resistance.

8. Keywords

8.1 load and resistance factor design (LRFD); reference resistance; wood-based

APPENDIXES

(Nonmandatory Information)

X1. COMMENTARY TO THE TEXT

X1.1 *Commentary to the Introduction:*

X1.1.1 Load and resistance factor design (LRFD) is a subset of a broader design methodology known as reliability-based design (RBD). The distinction between the two design procedures is significant. RBD implies, and often calculates, quantities related to the reliability of a member under a given set of conditions for a given reference period. A higher reliability corresponds to a lower probability of failure. One practical concern that arises when one attempts to apply RBD to real structural applications is that the calculations must idealize both the loads and the structural system response to reduce it to a mathematically tractable problem. This idealization process reduces the final calculation to a theoretically interesting, but often inapplicable, number. LRFD was developed by selecting a few of the basic concepts of RBD and using them to develop a format that is similar in many ways to current (allowable stress) design. LRFD provides incremental improvements in the design process in this way. The improvements provided by LRFD include the following:

X1.1.1.1 Consideration of the variability of various types of loads when assessing safety factors.

X1.1.1.2 Consideration of the consequences of various potential failure modes in a structure.

X1.1.1.3 Material resistance values that relate more closely to test data (member capacities).

X1.1.1.4 Consideration of resistance variability.

X1.1.2 Previous standards for developing allowable properties for many types of wood-based products directed the user to various ways of computing a population lower fifth-percentile estimate. This single number was the basis for an allowable strength property assignment. At the other extreme, a realistic RBD would require an accurate definition of a large portion of the lower tail of the material distribution and a large portion of the upper tail of the load distribution. LRFD requires somewhat more information than current procedures (for example, reference values and variability) but substantially less than RBD. In the most advanced LRFD procedures in use today, one needs only a distribution type and the parameters that describe that distribution. Refinements of these procedures suggest that estimates of the distribution and its parameters give the most accurate reliability estimates when they represent a tail portion of the distribution rather than the full distribution. This reflects the fact that, for common building applications, only the lower tail of the resistance and upper tail of the load distribution contribute to failure probabilities.

X1.1.3 Simulations have shown that the assumed distribution type can have a strong effect on computed LRFD resistance factors. However, much of this difference is due to the inability of standard distribution forms to fit the tail data precisely. By standardizing the distribution type, this procedure provides a consistent means for deriving these factors. In addition, by permitting tail fitting of the data, it provides a way of fitting data in this important region that is superior to full-distribution types.

X1.1.4 While the two-parameter Weibull distribution is the underlying basis for these calculations, the user of this specification is not burdened with applying statistical decisions. For LRFD purposes, the user must calculate the shape and scale parameters for the fitted Weibull distribution using the equations in the specification. All remaining steps in the calculations of a reference resistance are spelled out in the equations of the specification.

X1.2 *Commentary to Section 1, Scope*—The calculation procedures identified in this specification are common statistical procedures. This specification gives the user a document for all calculations necessary to develop LRFD reference resistances. Due to the sensitivity of reliability to changes in some of the parameters, these procedures offer a limited set of options to ensure that LRFD reference resistances are generated in a consistent manner.

X1.3 *Commentary to 4.1*—Some wood-based products exhibit extremely low variability when tested on a batch basis. On this basis, one would compute, for example, a fifth percentile that may be as high as 90 % of the mean value, as compared with a computed fifth percentile that may be less than 50 % of the mean value for a product with a substantially higher variability. The warning provided in this section is intended to caution the user of this specification to be certain that either the sampling plan or the daily quality control procedures are sufficiently sensitive to reflect population shifts caused by factors such as subtle manufacturing changes or shifts in material sources.

X1.3.1 *Commentary to* 4.1.2—Some test programs include a large number of replications of a single test cell. However, it is more common to develop a testing plan that includes a small number of replications in each test cell, repeating the testing across several configurations. For example, a joist hanger manufacturer might test less than ten replications of a given configuration, but the test is repeated across a range of wood species or hanger depths, or both. For such cases, it is advantageous to be able to pool the data from the various test cells to minimize the data confidence penalty. One technique for verifying the appropriateness of pooling across several test cells is to conduct pairwise significance tests using the Student "T" test. For this test, it is proposed that the minimum significance level be established at the 0.10 level. Another technique often used for data pooling is regression analysis.

X1.4 *Commentary to Section 5, Testing*—While the most desirable and reliable method of defining reference resistance for a given property is by the direct testing of representative materials, estimation methods may be used when such data are not available. The preferred method of defining the characteristics for missing data is through the use of a known physical relationship. For example, Weibull's theory[5] can be used to estimate reference resistance values for untested sizes of a certain product. Statistical relationships may be used in the case in which data are missing and no sufficiently reliable physical relationship exists. Linear or nonlinear curve fitting methods can be applied to define the statistical relationship between a given property and the influencing variables.

X1.5 *Commentary to Section 6, Reference Resistance for LRFD:*

X1.5.1 The basis for establishing many of the allowable stresses for wood-based products has traditionally focused on the population lower fifth percentile. The primary emphasis of this section is on these types of values. Some classes of products or types of stresses (that is, connections and compression perpendicular to grain) have established stresses based on an average (or mean) value or based on serviceability criteria rather than an ultimate limit, or both, in the past. Regardless of past procedures, a resistance distribution is necessary for a reliability-based procedure.

X1.5.2 Eq 4 is the equivalent result of two alternative derivations. Eq 4 is based on a graph of R_n/F_x that was generated across a range of load ratios for three distinct live-load cases (occupancy floor, snow roof, and non-snow roof), where R_n and F_x come directly from the LRFD and ASD design equations:

$$LRFD: \lambda\phi R_n \geq 1.2\,D + 1.6\,L \tag{X1.1}$$

$$ASD: K_d F_x \geq D + L$$

where:

λ = time effect factor,
ϕ = resistance factor,
R_n = reference resistance,
D, L = dead and live load effects, respectively,
K_d = load duration factor (ASD), and
F_x = allowable stress (ASD).

X1.5.3 The factor in the numerator of Eq 4 is in the range from 2.1 to 2.2 and resulted from the application of engineering judgment as a balance of increases for floors at low *L/D* ratios versus decreases for non-snow roofs at higher *L/D* ratios.

X1.5.4 In what may be called the second derivation, the precise factor of 2.16 happens to be the algebraic solution for the ratio of R_n/F_x for $L/D = 3$, $\lambda = 0.80$, and $K_d = 1.15$. However, this algebraic equivalent is not to be confused as the basis for Eq 4.

X1.6 *Commentary to 6.5, Data Confidence Factor,* Ω—This factor is based on the ratio of binomial confidence bounds for the reference resistance. More specifically, it is the ratio of the specified percentile with 75 % confidence to the estimate with 50 % confidence. Note that Ω is chosen based on the sample size of the complete data set, even if tail fitting is used.

X1.7 *Commentary to 6.6, Reliability Normalization Factor,* K_R*:*

X1.7.1 The objective of the conversion to an LRFD format is to provide the designer with a simple, easy-to-use procedure. For the convenience of the designer, specified resistance factors, ϕ_s, are given in the LRFD specification. In order to keep the number of different ϕ_s values to a minimum, an adjustment to the resistance is necessary because the computed resistance factors, ϕ_c, corresponding to specific target reliabilities, generally differ from the specified resistance factors. To attain the target reliability, the application of a reliability normalization factor, K_R, is required in the development of tabulated resistances.

X1.7.2 The use of the reliability normalization factor represents a reliability-based conversion. The fundamental relationship involving K_R is provided for the example case of a bending member.

X1.7.3 Consider the LRFD equation as applied to format-converted resistance:

$$\lambda\phi_s R_n \geq \Sigma\gamma_i Q_i \tag{X1.2}$$

where:

ϕ_s = specified resistance factor,
γ_i = load factor for load type, i, and
Q_i = load effect for load type, i.

X1.7.4 Next, consider the same relationship when the resistance side meets a computed level of reliability using the computed resistance factor, ϕ_c:

$$\lambda\phi_c R_n \geq \Sigma\gamma_i Q_i \quad \text{(X1.3)}$$

X1.7.5 Since it is desired to obtain the same target reliability by both equations, the first must be adjusted by the reliability normalization factor, that is:

$$\lambda\phi_s K_R R_n = \lambda\phi_c R_n \quad \text{(X1.4)}$$

from which the definition of the reliability normalization factor is obtained by the following ratio:

$$K_R = \phi_c/\phi_s \quad \text{(X1.5)}$$

X1.7.6 The designer need not be concerned with the relationship between ϕ_c and ϕ_s, since K_R is incorporated in the tabulated values. Reliability normalization is thus transparent to the designer.

X1.7.7 K_R equations are generated by applying first-order, second-moment, Level 2 reliability methods using the Rackwitz-Fiessler algorithms.[7] The procedure is the following: Choose a target reliability index, β, and conduct the reliability analysis across a range of CV_w values. Plot the calculated ϕ versus CV_w from these results to check for consistency and tabulate the ϕ_c as a function of CV_w. Table 2 is an example of some specified resistance factors for an LRFD specification. Selected target reliability indices are based on many technical parameters and judgments. For example, the general level of the index is influenced by the underlying reliability calculation methods and on assumed distribution type. Other parameters that influence the relationship between calculated ϕ and CV_w, such as target load cases (for example, live or snow), appropriate load ratios (for example, ratios of live-to-dead or snow-to-dead loads), and tributary areas are also important. The target indices were chosen based on a 50-year life for a structure. Also examined were a range of commonly used primary structural members. A target reliability index of 2.4 was used for the bending strength properties of fifth-percentile-based products. For the purposes of determining K_R, the reliability analysis used the dead plus live load case with the load distributions given in *Load and Resistance Factor Design for Engineered Wood Construction—A Pre-Standard Report*.[6] This load case and the live-to-dead ratio of 3 are considered an appropriate basis for evaluating the reliability of wood-based materials used in structures addressed within the scope of ASCE 7-02.

X1.7.8 The target reliability index was computed for the reference case in which the ASTM-specified divisor is 2.1. For other cases, in which the ASTM-divisor differs significantly from 2.1, it is believed that the differences attempt to quantify factors to account for discrepancies between stress calculations in the ASTM test versus those in the structural-size member. An example of this is the larger divisor for shear, in which the results from the standard test specimen, a 4-in.^{2} shear block, do not correlate directly with those on structural-size members. Thus, for the purposes of this specification, it is assumed that differing ASTM-divisors do not produce differing target reliability indices, but merely adjust for other factors not addressed elsewhere in the procedures. On this basis, it is necessary to include the same scaling in LRFD as is used in ASD.

X1.7.9 Tabulated K_R values for bending were determined by this procedure. Reliability normalization factors for other properties were developed by scaling bending K_R values on the basis of ASTM ASD adjustment factors.

X1.7.10 The scaling provides an equivalent ϕ_c for the other properties as follows:

$$\phi_c = [2.1/A]\,[(K_R)(\phi_s)]_{\text{bending}} \quad \text{(X1.6)}$$

where A is provided in the following table:

Material Property	Allowable Stress Design Adjustment Factor, *A*
Compression, bearing	1.9
Bending, tension	2.1
Shear—glulam, SCL (full-size basis)	2.1
Shear—Lumber (shear-block basis)	2.1
Shear—SCL (shear-block basis)	3.15
Shear—I-Joist	2.37

For example, Table 3 provides a K_R value of 1.212 for bending at CV = 17 %.

X1.7.11 The K_R value for compression at the same CV is determined as:

$$\phi_c = [(2.1)/(1.9)]\,[(1.212)(0.85)] = 1.139 \quad \text{(X1.7)}$$

$$K_R = \phi_c/\phi_s = 1.139/0.9 = 1.265$$

X1.7.12 Compared to allowable stress design, several changes in LRFD (choice of β, load factoring, time effect factor, and resistance CV_w) dictate that most designs will change to a degree. The factors of Table 3 were computed after many iterations of these variables. These final factors generally minimize the changes (compared to ASD) introduced by the reliability-based LRFD system. A nearly identical member design (compared to ASD) will occur when the application is a snow-loaded roof, S/D = 3 and $CV_w \approx$ 17 %. The reasoning behind the decisions underlying the Table 3 values is discussed in Gromala, et al.[8]

NOTE X1.1—*Example Derivation of LRFD Reference Resistance*—The following example provides the LRFD reference resistance for a bending member with a target reliability of β = 2.4. As shown in Eq 1, computing a reference resistance (R_n) requires the calculation of three other quantities (R_p, Ω , and K_R).

Calculating R_p—As shown in Eq 2, R_p is a function of the two parameters of the Weibull distribution (α, and η). Appendix X2 provides two accepted methods for computing these parameters. For an example data set containing the failure stresses of 100 bending specimens, the shape parameter (α) is 5.75, and the scale parameter (η) is 3425 psi. The Weibull parameters are substituted into Eq 2 to compute R_p. The computed fifth percentile is 2043 psi for this data set.

Calculating Ω—Table 1 provides numerical values of Ω for various sample sizes and coefficients of variation. For the example data set, n = 100 and the coefficient of variation is computed directly from the shape parameter as shown in Eq 3. For α = 5.75, this yields a CV_w of 0.20, and Ω = 0.94.

[7] Thoft-Christensen, P., and Baker, M. J., *Structural Reliability Theory and Its Applications*, Springer-Verlag, New York, NY, 1982.

[8] Gromala, D. S., Sharp, D. J., Pollock, D. G., and Goodman, J. R.,“ Load and Resistance Factor Design for Wood: The New U.S. Wood Design Specification,” *Proceedings 1990 International Timber Engineering Conference*, Tokyo, Japan, 1990.

Calculating K_R—Table 3 provides numerical values of K_R for various CV_w values. For this example with CV_w of 0.20, the K_R is 1.168. From Eq 1, the LRFD reference resistance is determined as follows:

$$R_n = [(0.94)\ (1.168)\ (2043)] \quad \text{(X1.8)}$$

$$R_n = 2243 \text{ psi}$$

X1.8 *Commentary to 6.5:*

X1.8.1 The format conversion factor of 1.5 for stability is to be applied to the design modulus of elasticity used in ASD for stability (not to the average *MOE* used for deflection calculations). Conceptually:

$$\text{For ASD:} \quad E_{min} = E_{05}/1.66 \quad \text{(X1.9)}$$

$$\text{For LRFD:} \quad \textit{Multiply by } K_F = 1.5 \quad \text{(X1.10)}$$

$$E_{min} = (E_{05}/1.66) \times 1.5$$

$$= (0.904 \times E_{05})$$

X1.8.2 The rationale behind this interpretation is that the equations for K_{bE} and K_{cE} contained in the 2001 *NDS* beam and column stability provisions adjust tabulated modulus of elasticity (E) values to fifth percentile shear-free E values divided by a 1.66 safety factor. In the 2005 *NDS*, K_{bE} and K_{cE} equations are replaced with a reference to tabulated E_{min} values, which are being added to the *NDS* (for poles and piles) and *NDS Design Value Supplement* (for lumber or glulam). By tabulating E_{min} values (fifth percentile shear-free E values divided by a 1.66 safety factor), these provisions for beam and column stability equations will be significantly simplified. Generic presentation of column and beam behavioral equations using E_{min} values are applicable for both ASD and LRFD, eliminating the need for two different formats for the same behavioral equations.

X1.8.2.1 E_{min} values for sawn lumber are estimated as follows:

$$E_{min} = \frac{1.03E(1 - 1.645(COV_E))}{1.66} \quad \text{(X1.11)}$$

X1.8.3 The format conversion factor, $K_F = 1.5$, is based on a calibration at the reference condition assuming a live load (L) to dead load (D) ratio of $L/D = 3$. The calibration was done as follows:

$$\text{ASD: } D + L = E_{min} \quad \text{(X1.12)}$$

$$D + 3D = E_{min}$$

$$4D = E_{min}$$

$$\text{LRFD: } 1.2D + 1.6L = K_F \phi_s E_{min} \quad \text{(X1.13)}$$

$$1.2D + 1.6(3D) = K_F \phi_s E_{min}$$

$$6D = K_F \phi_s E_{min}$$

Substituting and solving for K_F:

$$K_F = \frac{6}{4}/\phi_s = 1.5/\phi_s$$

X1.9 *Commentary to Table 2, ϕ-factor for Shearwalls and Diaphragms:*

X1.9.1 Precise calibration of ϕ for shear walls and diaphragms for the wind and seismic load cases can be derived from LRFD and ASD design equations as follows:

$$\text{LRFD:} \quad \lambda \phi R_n \geq 1.6\ W \quad \text{(X1.14)}$$

$$\text{ASD:} \quad K_d F_x \geq 1.0\ W \quad \text{(X1.15)}$$

where:
λ = time effect factor,
ϕ = resistance factor,
R_n = reference resistance,
W = wind load effect,
K_d = load duration factor (ASD), and
F_x = allowable stress (ASD).

X1.9.2 A calibration value of ϕ = 0.8 is computed for the wind load case from solution of Eq X1.14 and X1.15 for K_d = 1.0 (because shear wall and diaphragm design values are based on 10-min load duration), λ = 1.0 (for wind load case), and $R_n/F_x = 1.6/\phi = 2.0$.

X1.9.3 LRFD and ASD design equations for seismic (earthquake) load effects are:

$$\text{LRFD:} \quad \lambda \phi R_n \geq 1.0\ E \quad \text{(X1.16)}$$

$$\text{ASD:} \quad K_d F_x \geq 0.7\ E \quad \text{(X1.17)}$$

where:
E = earthquake load effects.

X1.9.4 A calibration value of ϕ = 0.71 is computed for the seismic load cases from solution of Eq X1.16 and X1.17 for K_d = 1.0 (because shear wall and diaphragm design values are based on 10-min load duration), λ = 1.0 (for earthquake load case), and $R_n/F_x = 1.6/\phi = 2.0$.

X1.9.5 Based on the judgment of the committee, the value of ϕ = 0.8 is considered appropriate for shear walls and diaphragms–for both wind and seismic load effects. This value (ϕ = 0.8) provides exact calibration between ASD and LRFD for wind load effects. The slight 12 % benefit for LRFD relative to ASD for earthquake load effects is considered to be within an acceptable range. Note that differences between LRFD and ASD result from inherent differences in load factors for wind and earthquake load effects.

X1.9.6 One option considered for minimizing the difference between LRFD and ASD was assignment of different values of ϕ for earthquake and wind effects to provide exact calibration. Such an approach was considered to be unnecessarily complicated and inconsistent with fundamental approaches in Specification D 5457 to minimize differences in ϕ for the same stress mode. In general, a single ϕ is assigned to individual properties (in this case, shear wall and diaphragm shear) independent of load effects.

X1.9.7 To assist in judging whether the slight 12 % benefit for LRFD relative to ASD for the seismic load case was acceptable, ratios of shear wall demand (due to earthquake load effects) divided by shear wall design capacity were compared to historical practice (from 1955 to the present). In general, demand-to-capacity ratios have been increasing in high seismic areas–even if the 12 % benefit to LRFD is considered. Increasing demand-to-capacity ratios can be attributed to new mapping and "near-fault" conditions recognized in modern building codes as well as to reduced capacity for shear walls with height-to-length ratios less than 2:1. Increasing demand-to-capacity ratios suggest that modern building codes require greater amounts of shear resistance to resist earthquake load effects than they did previously.

X1.10 *Commentary to 6.7.4, Format Conversion for ASD Deformation-Based Compression Perpendicular to Grain Values*—Wood compression perpendicular to grain stresses are based on serviceability criteria from testing of small specimens (Test Methods D 143, square cross-section block, 2 in. loading block). However, in many cases, these allowable stresses are being applied more broadly. In some compression perpendicular to grain applications, especially where laterally unsupported tall/narrow sections are used, failure modes, such as instability or splitting, can occur. These failure modes have been demonstrated in short-term tests to occur at compression perpendicular to grain stress levels as low as 1.5 times the ASD value for compression perpendicular to grain. The format conversion for compression perpendicular to grain is calibrated to "normal" duration of load (that is, 10 years). However, when coupled with the time effect factor for short-term loads (wind and seismic), the effective compression perpendicular to grain design value is higher under LRFD. This increase has been debated and has been judged to be reasonable for these design cases. However, under these circumstances, designers must be certain to check the failure modes of buckling or splitting that may now control the design. Alternatively, the designer may choose to brace the tall/narrow member at the bearing to prevent this mode from occurring.

X1.10.1 One method to compute buckling capacity in the perpendicular to grain direction for ASD may be done by using an elastic-buckling (Euler) type formula similar to that now used for visually graded lumber. This calculation could supplement the standard ASD Fcperp calculation. In the calculation, the relevant modulus of elasticity is the transverse modulus (often assumed to be $E/20$) and the relevant dimensions (relative to buckling direction) would also be substituted.

X2. PARAMETER ESTIMATION PROCEDURES

X2.1 *Method of Maximum Likelihood:*

X2.1.1 This method may be used for parameter estimation with either complete or lower tail data sets. The method also defines convergence criteria for this iterative procedure. Use first n_c of n data (after ranking), as follows:

$$n_s = n - n_c \tag{X2.1}$$

where:

n_c = number of data values used in the analysis ($n_c = n$ for complete data sets), and
n_s = number of data values not used.

Each such data point is assigned the value r_s, the maximum data value used.

X2.1.2 Calculate the CV ($s/\bar{x}$) from the available data. This CV is to be used only as an initial value for the estimation procedure. Let $(1/\alpha)$ approximate CV:

$$(1/\alpha) = \frac{\Sigma r_i^{\alpha}\, ln(r_i) + n_s r_s^{\alpha}\, ln(r_s)}{\Sigma r_i^{\alpha} + n_s r_s^{\alpha}} - \frac{\Sigma ln(r_i)}{n_c} \tag{X2.2}$$

X2.1.3 Then iterate the above equation, updating α, for 100 iterations or until the change in the absolute value of $(1/\alpha)$ <0.00002 (ln is natural logarithm). Then,

$$\eta = [(\Sigma r_i^{\alpha} + n_s r_s^{\alpha})/n_c]^{(1/\alpha)} \tag{X2.3}$$

where all summations are from $i = 1$ to n_c.

X2.2 *Method of Least Squares:*

X2.2.1 This method may be used for parameter estimation with either complete or lower tail data sets. Use first n_c of n data (after ranking).

$$n_c = \text{number of data values used for analysis} \tag{X2.4}$$

$$(n_c = n \text{ for complete data sets})$$

$$\text{set } x_i = ln(-ln[1 - \{(i - 0.3)/(n + 0.4)\}])$$

$$\text{independent variable}$$

$$y_i = ln\,(r_i) \text{ dependent variable}$$

where ln = natural logarithm.

$$(1/\alpha) = \frac{n_c \Sigma x_i y_i - \Sigma x_i \Sigma y_i}{n_c \Sigma x_i x_i - \Sigma x_i \cdot \Sigma x_i} \tag{X2.5}$$

and

$$\eta = \exp[(\Sigma y_i)/n_c - (1/\alpha)(\Sigma x_i)/n_c] \tag{X2.6}$$

where all summations are from $i = 1$ to n_c.

X3. EXACT COEFFICIENT OF VARIATION CALCULATION METHOD

X3.1 Coefficient of variation can be calculated using the Weibull shape and scale parameters along with the use of Table X3.1 or an equivalent computerized function.

$$CV_w = \frac{\eta[\Gamma\{1 + 2(1/\alpha)\} - \Gamma^2\{1 + (1/\alpha)\}]^{1/2}}{\eta\Gamma[1 + (1/\alpha)]} \tag{X3.1}$$

TABLE X3.1 Gamma Function: Values of
$\Gamma(n) = \int_0^\infty e^{-x}x^{n-1}dx$; $\Gamma(n+1) = n\Gamma(n)$

n	$\Gamma(n)$	n	$\Gamma(n)$	n	$\Gamma(n)$	n	$\Gamma(n)$
1.00	1.00000	1.25	0.90640	1.50	0.88623	1.75	0.91906
1.01	0.99433	1.26	0.90440	1.51	0.88659	1.76	0.92137
1.02	0.98884	1.27	0.90250	1.52	0.88704	1.77	0.92376
1.03	0.98355	1.28	0.90072	1.53	0.88757	1.78	0.92623
1.04	0.97844	1.29	0.89904	1.54	0.88818	1.79	0.92877
1.05	0.97350	1.30	0.89747	1.55	0.88887	1.80	0.93138
1.06	0.96874	1.31	0.89600	1.56	0.88964	1.81	0.93408
1.07	0.96415	1.32	0.89464	1.57	0.89049	1.82	0.93685
1.08	0.95973	1.33	0.89338	1.58	0.89142	1.83	0.93969
1.09	0.95546	1.34	0.89222	1.59	0.89243	1.84	0.94261
1.10	0.95135	1.35	0.89115	1.60	0.89352	1.85	0.94561
1.11	0.94739	1.36	0.89018	1.61	0.89468	1.86	0.94869
1.12	0.94359	1.37	0.88931	1.62	0.89592	1.87	0.95184
1.13	0.93993	1.38	0.88854	1.63	0.89724	1.88	0.95507
1.14	0.93642	1.39	0.88785	1.64	0.89864	1.89	0.95838
1.15	0.93304	1.40	0.88726	1.65	0.90012	1.90	0.96177
1.16	0.92980	1.41	0.88676	1.66	0.90167	1.91	0.96523
1.17	0.92670	1.42	0.88636	1.67	0.90330	1.92	0.96878
1.18	0.92373	1.43	0.88604	1.68	0.90500	1.93	0.97240
1.19	0.92088	1.44	0.88580	1.69	0.90678	1.94	0.97610
1.20	0.91817	1.45	0.88565	1.70	0.90864	1.95	0.97988
1.21	0.91558	1.46	0.88560	1.71	0.91057	1.96	0.98374
1.22	0.91311	1.47	0.88563	1.72	0.91258	1.97	0.98768
1.23	0.91075	1.48	0.88575	1.73	0.91466	1.98	0.99171
1.24	0.90852	1.49	0.88595	1.74	0.91683	1.99	0.99581
						2.00	1.00000