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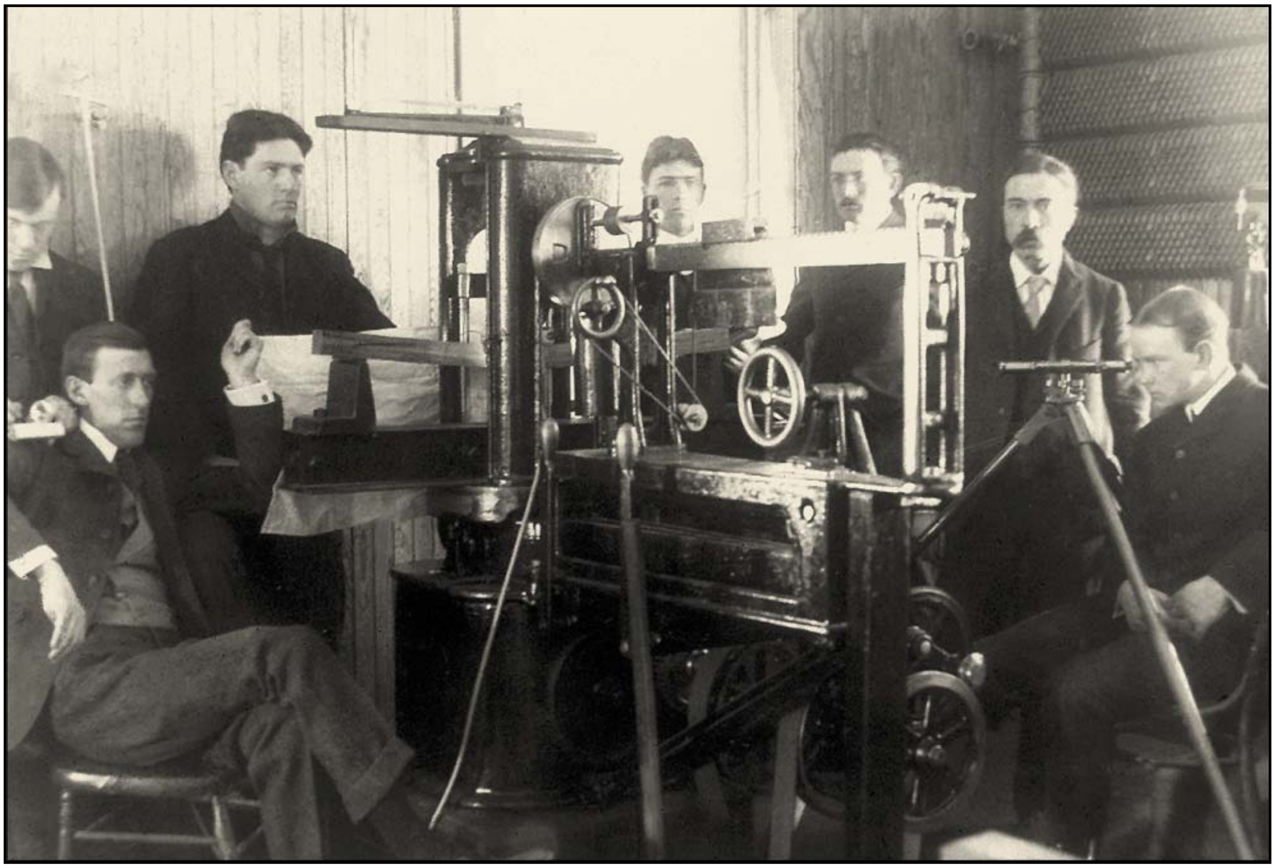
Evolution of Standardized Procedures for Adjusting Lumber Properties for Change in Moisture Content

David W. Green
James W. Evans



Abstract

This paper documents the development of procedures in American Society for Testing and Materials standards for adjusting the allowable properties of lumber for changes in moisture content. The paper discusses the historical context of efforts to establish allowable properties on a consensus basis, beginning in the 19th century. Where possible, the reasons for proposed changes in the standards are presented. The goal of this work is to foster a better understanding of how current standards have evolved and to promote reconciliation of conflicting property assignment procedures between current standards.

Keywords: Moisture content, modulus of elasticity, modulus of rupture, compression parallel to grain, compression perpendicular to grain, tension parallel to grain, shear parallel to grain, American Society for Testing and Materials

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Cover: Class at Yale University, around 1906.
Harry D. Tiemann is second from right.

Conversion factors

Inch–pound unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
pound force/square inch (lb/in^2)	6.894	kilopascal (kPa)
pound force/square foot (lb/ft^2)	47.88	pascal (Pa)
temperature, °F (T_F)	$[T_F – 32]/1.8$	temperature, °C

Preface

Of the environmental factors that affect structural design with wood, one of the most important is moisture content. Although the mechanical properties of small clear specimens generally increase with drying, the properties of structural lumber may not. In the United States, differences of opinion over the objectives of a lumber testing program, and therefore over whether to base allowable properties on tests of small clear specimens adjusted for grade and other factors or directly on tests of full-size structural members, have influenced efforts to establish lumber property standards since the 19th century. Efforts to harmonize the benefits of the two approaches have sometimes led to confusion as to the basis for adjusting allowable properties for change in moisture content and to inconsistencies between different standards.

The primary objective of this paper is to document the historical development of procedures in American Society for Testing and Materials (ASTM) standards for adjusting the allowable properties of lumber for changes in moisture content. Our goals are to foster a better understanding of how current standards have evolved and to promote reconciliation of conflicting property assignments.

We first review the historical context for establishing lumber properties on a consensus basis, beginning in the 19th century. Then, we follow the development of factors for adjusting allowable properties for change in moisture content, beginning with ASTM D245, which was established in 1926. Where possible, we try to document reasons for these developments. We also try to chronicle and explain the development of adjustment factors in ASTM D2915, established in 1970, and ASTM D1990, established in 1991. Current editions of these standards show some significant differences in adjustment factors for dimension lumber when properties are adjusted from green to 12% moisture content. These factors are shown in a table following this text.

We recognize that moisture adjustment procedures are not the only differences between these ASTM standards, but they are a significant difference. Because both ASTM D1990 and D2915 start with test results on full-size lumber, these may be the easiest standards to reconcile.

Ratio of property at 12% moisture content to that of green dimension lumber by various ASTM standards[a]

Standard	MOR	UTS	MOE	UCS	Shear	C–perp
D245–99	1.35	1.35	1.20	1.75	1.13	1.50
D2915–98[b]	1.33	1.33	1.20	1.91	1.17	1.00
D2555–98[c]	1.69	—	1.25	1.99	1.47	2.03
D1990–97			1.18		—	—
6,000 lb/in^2	1.39	1.09	1.18	NA	—	—
5,000 lb/in^2	1.33	1.07	1.18	NA	—	—
4,000 lb/in^2	1.26	1.04	1.18	1.65	—	—
3,000 lb/in^2	1.13	1.00[d]	1.18	1.53	—	—
2,000 lb/in^2	1.00[d]	1.00[d]	1.18	1.30	—	—
1,000 lb/in^2	1.00[d]	1.00[d]	1.18	1.00[d]	—	—

[a] MOR is modulus of rupture, UTS ultimate tensile stress, MOE modulus of elasticity in bending, UCS ultimate compressive stress, C-perp compression perpendicular to grain, and NA not applicable. NA indicates that the green value is higher than the applicable range of adjustment (9,600 lb/in^2 for MOR, 8,400 lb/in^2 for UTS, and 4,400 lb/in^2 for UCS); significant error may occur. Arrow (
under D1990–97 may vary with initial green strength. Refer to strength values listed in the table.

[b] Adjusting over this moisture content range may not be within the intent of the standard (see text).

[c] D2555 values are the average for all softwood species, for small clear specimens (App. E).

[d] Adjustment is 1.0 below 2,400 lb/in^2 for MOR, 3,150 lb/in^2 for UTS, and 1,400 lb/in^2 for UCS.

Contents

Evolution of Standardized Procedures for Adjusting Lumber Properties for Change in Moisture Content

David W. Green, Supervisory Research General Engineer
James W. Evans, Supervisory Mathematical Statistician
Forest Products Laboratory, Madison, Wisconsin

Introduction

Most properties of small clear specimens of wood increase significantly as moisture content decreases (Fig. 1). The properties of structural lumber may or may not increase with drying (Fig. 2). Historically, allowable properties in the United States were based on tests of small clear specimens in American Society for Testing and Materials (ASTM) standard D245. However, moisture adjustment procedures in D245 were not necessarily based on clear wood tests. The combination of basing properties on clear wood data and basing some adjustment procedures on tests of full-size members with defects has created confusion in the literature (Madsen 1992) and could lead to erroneous decisions in future engineering standards. Furthermore, the adoption of ASTM D1990 for deriving allowable properties based on tests of full-size structural members resulted in three ASTM standards (D245–99, D1990–97, and D2915–98) with procedures for adjusting lumber properties for change in moisture content. These procedures do not always produce identical results, and any consistency between them in regard to moisture content adjustment procedures is not apparent.

The primary objective of this paper is to document the historical development of procedures for adjusting the allowable properties of lumber for changes in moisture content in ASTM standards. First, we describe the early development of standardized procedures for assigning allowable lumber properties as a basis for understanding why some moisture adjustment procedures have evolved in different ways. We then present the history of standardized moisture content adjustment procedures for six properties for which allowable properties are currently assigned: modulus of elasticity in bending and strength in bending, tension parallel to grain, compression parallel and perpendicular to grain, and shear parallel to grain. Finally, we present recommendations to improve the consistency of adjustment procedures between different standards.

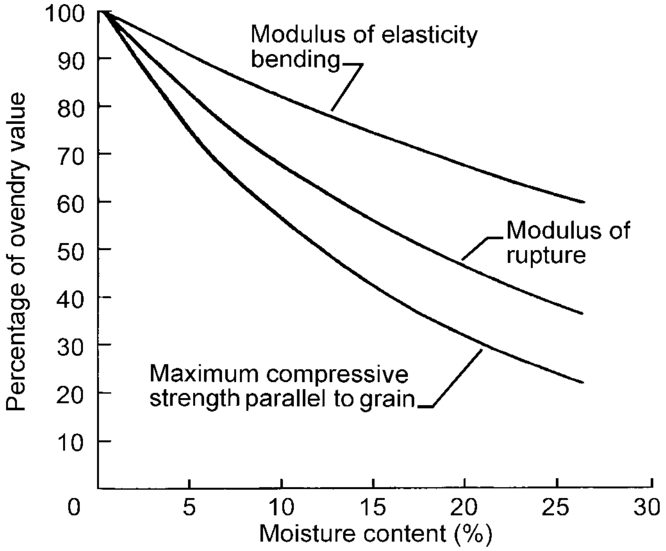


Figure 1—Traditional model for predicting effect of moisture content on mechanical properties of small clear specimens (Panshin and de Zeeuw 1970).

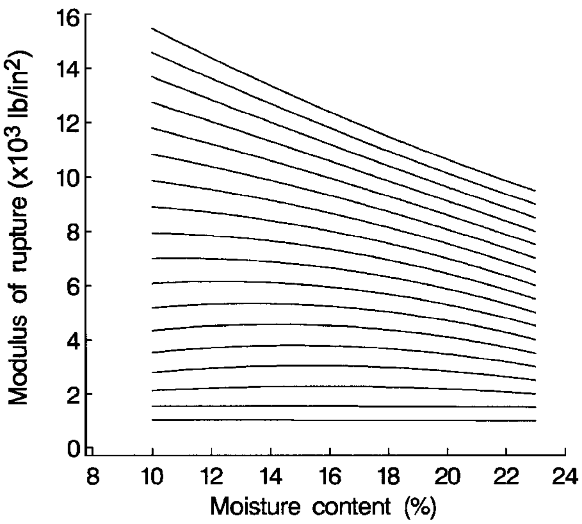
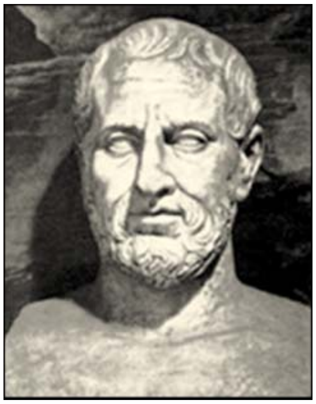


Figure 2—Quadratic surface model for predicting effect of moisture content on bending strength of lumber parallel to grain (Green and Evans 1989).

It is important to consider the assumed adjustment factors within the historical context of when the decisions were made. Early emphasis was placed on standardization of allowable properties for what today is primarily considered “heavy timber.” Over much of the past century, “framing lumber,” lumber primarily intended for use in housing, did not have assigned properties. Beginning in the late 1950s, the development of engineered roof systems, the metal-plate wood truss, and more recently, the wood I-joist, have changed the focus of standards and the ways in which adjustment procedures are handled in ASTM standards. In the 1960s, lumber dimensions were standardized for green and dry lumber (Wood 1964). All these changes interacted with changes proposed for moisture content adjustments.


Theophrastus

Research on the properties of wood and the effect of moisture content on these properties did not originate in the United States. For example, in ancient Greece, Theophrastus (372–287 B.C.) conducted comprehensive investigations into the properties and utilization of wood (Tsoumis 1995). Although Theophrastus apparently did not discuss the effect of moisture content on mechanical properties, he did comment on its effect on shrinkage and utilization. Booth (1964) summarized developments in Europe during the 17th and 18th centuries to determine the mechanical properties of timbers (Table 1). Galileo is often called the “father of strength of materials,” and Booth recommended that Petrus van Musschenbroek be bestowed a similar title for undertaking the first comprehensive work to determine the properties of timber. Some previous researchers had concluded that “dryness” could affect wood properties. Booth, however, credited William Emerson (in 1758) as the first to correctly conclude that “wood is likewise weaker when it is green and strongest when thoroughly dried,” a conclusion with which Musschenbroek disagreed. Georges Buffon (1707–1788) performed one of the most comprehensive series of tests that had been undertaken on the mechanical properties of wood. Included were a series of tests to compare the properties of small clear specimens with those of large members. After carefully testing more than 1,000 small specimens and being extremely careful to ensure that the specimens contained no knots or other defects, Buffon concluded that it was not possible to predict the properties of full-size timbers containing defects from tests of small specimens, and he began a series of tests on full-size structural members. His conclusion that tests of small specimens (without further adjustment) cannot be used to predict the properties of full-size members raised a


William Emerson


Georges Buffon

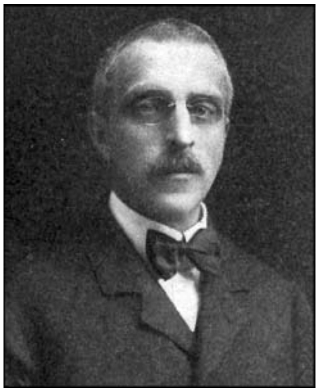
Table 1—Summary of timber testing developments in Europe in the 17th and 18th centuries[a]

Name	Topic	Date
Galileo	Description of tension test	1638
Mariotte	Ultimate load of small cantilever beam and small tension specimens	1680
Hooke	Load–deformation behavior of cantilever	1678
Parent	Ultimate load of small oak and fir beams fixed at one end, fixed at both ends, and simply supported	1707
Musschenbroek	Development of tensile test machine; tension tests of various free parts; tension strength of various species; drawings of failures; effect of moisture content and density on strength; buckling of a column	1729–1762
Buffon	Effect of growth rate on density; tabular recording of test results; tests of large beams; load–deflection behavior of beams; effect of duration of load	1740, 1741
Duhamel	Distribution of stresses in a beam	1742
Emerson	Correct effect of moisture on strength	1758
Girard	Development of test machine for large bending and compression specimens; tests on large compression specimens	1798

[a] Booth 1964.

question that was to continue into the 20th century. Early researchers in the United States conducting tests on wood properties would have been aware of European developments.

Prior to 1895, grading procedures and property assignment procedures for solid-sawn structural lumber sold in the United States were not standardized. Rather, lumber testing procedures, visual grading procedures, and procedures for derivation of allowable properties were proprietary procedures developed by consulting engineers, college professors, and government scientists active in the field of timber engineering. The primary impetus for standardization of these procedures was the design of railway structures. In 1895, a committee of the American International Association of Railway Superintendents of Bridges and Buildings presented a report on the strength of bridge and trestle timbers (Berg and others 1907). This report included a summary, compiled by the chairperson, of all available property data collected from many sources from about 1870 to 1895. It also presented 15 recommendations by leading authorities on the strength of timbers, which included design equations. Three of these recommendations may be paraphrased as follows (App. A):


Walter G. Berg

- Recommendation 4: As a rule, a reduction of moisture content is accompanied by an increase in strength.
- Recommendation 5: Structures should generally be designed for the strength of green or moderately seasoned lumber of average quality, and not for a high grade of well-seasoned material.
- Recommendation 9: Beams cut from heartwood frequently season-check along their center and fail by longitudinal shear.

The committee recommended ultimate breaking stress for selected species based on their review of the available data (App. A). These properties were for the average conditions existing in railroad timber structures. The committee also recommended the following safety factors for converting the breaking stresses to allowable properties:

Tension, with and across grain	10
Compression, with grain	5
Compression, across grain	4
Transverse (bending), extreme fiber stress	6
Transverse (bending), modulus of elasticity	2
Shear, with and across grain	4

In the discussion of the existing data, the committee was highly critical of those using small specimens of clear wood to derive allowable properties, and complimentary of those using tests of full-size members (Berg and others 1907).

In 1886, Bernard E. Fernow was appointed chief of the Division of Forestry, the predecessor of the Forest Service. Fernow conceived a forestry program that contained as one of its major objectives a more comprehensive determination of the strength properties of the most important species of trees (Nelson 1971). Efforts to develop standardized procedures on a broader basis shifted toward this program. At this time, there was no general agreement in the United States on the purpose of timber test programs. Generally, the proponents of timber testing fell into one of two groups (Newlin 1927).

Some strongly felt that the primary purpose of timber test programs is to develop data needed by engineers and architects. These proponents thought that tests should be conducted on full-size structural members selected from the marketplace.

Others, including foresters, felt equally strongly that the primary purpose of a timber test program should be to reveal the average strength properties of various species and the effect of conditions of growth and other factors on these averages. This group became intimately associated with the idea that many tests of small specimens should be used to establish average values for the species. They thought that a large program to test full-size members would be quite expensive and impractical.

Each group tried to meet the demands of the other group to some extent. The testing program of the Division of Forestry from 1891 to 1909 generally incorporated both approaches.

In 1891, J.B. Johnson of Washington University in St. Louis, Missouri, formulated the first detailed testing program under Fernow's general plan. Although an engineer, Johnson emphasized the forestry aspects of the problem and primarily focused on tests of small (4- by 4-in.) specimens. His work ceased after about 5 years when the Division of Forestry appropriations for research were reduced.


Harold Betts

In 1902, Harold Betts joined the Division of Forestry and organized the first timber testing laboratory in Washington, D.C. (Nelson 1971). Later that year, Betts helped organize a second laboratory at Yale University in New Haven, Connecticut. In 1903, he organized laboratories at Purdue University in Lafayette, Indiana, and the

William K. Hatt

University of California at Berkeley. The Washington laboratory emphasized tests of Southern Pine. At Yale, Harry Tiemann began a comprehensive program of the influence of moisture on strength. At Purdue, William Kendrick Hatt emphasized the development of improved test methods and the testing of hardwoods from the central region of the United States. At Berkeley, Loren Hunt conducted tests on California structural timbers.

In 1905, another timber testing program was established at the University of Washington in Seattle, where Rolf Thelen conducted tests on western hemlock and Douglas-fir structural-size timbers. The following year, a laboratory was established at the University of Oregon in Eugene, where J.B. Knapp tested structural timbers for species native to the region. In 1908, a laboratory was established in Denver to test the strength of fire-killed timber.

McGarvey Cline

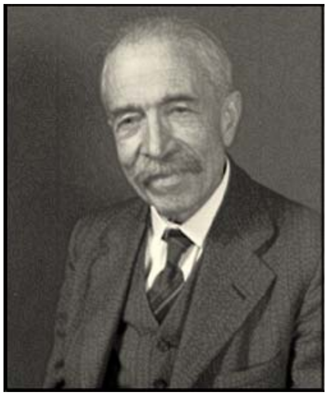
By 1905, W.K. Hatt of Purdue was in charge of the overall timber test program of the Division of Forestry. He trained several timber test engineers who later entered the Forest Service, including McGarvey Cline, the first director of the Forest Products Laboratory in Madison, Wisconsin, and John Newlin, who was in charge of timber mechanics at the Forest Products Laboratory. Hatt was of the opinion that the proper function of a government laboratory was to pursue both full-size tests of commercial timbers to provide engineering design data and tests of small specimens to provide insight into the relationship between management practices and wood properties (Newlin 1927). To incorporate all knowledge gained over the last 14 years and to standardize the program at the various laboratories, the Forest Service published Circular 38, *Instructions to Engineers in Timber Tests,* in 1905 (Hatt 1905).

The American Society for Testing and Materials (ASTM) was organized in Philadelphia on June 16, 1898, to consolidate the American membership in the International Association of Testing Materials, which had been organized in Munich in 1895 (ASTM Proceedings 1905). The ASTM was formed to promote the knowledge of the materials of engineering and the standardization of specifications and methods of testing. By 1905, ASTM had 21 committees, including the newly formed Committee Q on "Standard Specifications for the Grading of Structural Timber." Committee Q (which became Committee D7 in 1910) described their objective as follows:

> It is believed that the time has come for a comprehensive study and analysis of the grading of structural timbers, so as to arrive at a general understanding of the qualities of the various woods used for structural purposes, in order to standardize as far as possible, for the use of lumber manufacturers on one hand, and architects and engineers on the other hand, the various grades and qualities of woods. (ASTM Proceedings 1905)

The report further notes that one of the most important practical results of such a study would be to reduce the enormous waste that results, even in the practice of the most competent engineer. The work of the committee was to be organized into three areas: definition of structural timbers, standardization of trade names, and grading. Hermann Von Schrenk was chosen as chairperson. By 1907, the committee was organized into five subcommittees: Bridge and Trestle Timbers, Car Sills and Car Framing, Framing for Buildings, Ship Timbers, and Cross-Arms for Poles (ASTM Proceedings 1907).

Hatt was Committee secretary and a member of the Bridge and Trestle Timbers subcommittee (as was Fernow, then at Ithaca, New York). The 1908 meeting of Committee Q was held in conjunction with the meeting of the Bridge and Trestle Timber Committee of the American Railway Engineering and Maintenance of Way Association in Chicago (ASTM Proceedings 1908). Of particular note are three papers presented by Forest Service researchers: McGarvey Cline, Harry Tiemann, and Rolf Thelen.



Harry D. Tiemann

Cline's and Tiemann's papers dealt primarily with the relationship between loading rate and properties. Cline's paper, *Forest Service Tests to Determine the Influence of Different Methods and Rates of Loading on the Strength and Stiffness of Timber,* included strength at different rates of loading in an ordinary universal testing machine, strength under dead load, and resistance of wood to impact loads. Tiemann's paper, *The Effect of the Speed of Testing Upon the Strength of Wood and the Standardization of Testing for Speed,* provided more details on this subject and also included contemporary information on results obtained by non-Forest Service researchers. His own data were for small clear specimens, including both wet and kiln-dried material. Tiemann observed that the moisture–strength relationship in bending and in compression parallel to grain is a function of the speed of testing, with green specimens being more sensitive to rate of loading than are dry specimens.

In Thelen's paper, *The Structural Timbers of the Pacific Coast*, the test data on full-size timbers included both green and partially air-seasoned timbers. Thelen concluded the following:

> It has been found that in large timbers the seasoning process causes not only the loss of moisture but also the checking of the timber. Since it is impossible to determine the exact effect which this checking has on the strength of the timber, it is impossible to reduce the strength of the tested timber to that at some other conditioning of seasoning, even though we know exactly the effect of the moisture on the strength. (ASTM Proceedings 1908)

A more detailed discussion of this topic is given in Forest Service Circular 115 (Hatt 1907).

In 1910, the Forest Service timber testing program was centralized in the new Forest Products Laboratory in Madison, Wisconsin. A new work plan was formulated with the cooperation of Hatt. This work plan included an exhaustive study of the properties of clear wood for many American species. The plan was submitted to ASTM Committee D7, approved as a tentative standard in 1922, and established as standard D143–27, Standard Methods of Testing Small Clear Specimens of Timber, in 1927.

The dual emphasis on testing of full-size lumber was also maintained. A number of individual reports had been generated by the Division of Forestry since 1891 on the properties of individual species of structural timbers. A re-summary and correlation of all the major data available from the Forest Service test program on full-size timbers was published in 1912 as Forest Service Bulletin 108 (Cline and Heim 1912). The results of this phase of the program were felt to be particularly valuable in determining safe working stresses (allowable properties) and in preparing and revising grading rules. Bulletin 108, and some individual previous reports, contained some test data on the properties of both green and dry timbers. A standard testing procedure for full-size timbers (Fig. 3) was proposed to the ASTM D7 Committee and accepted as a tentative ASTM standard in 1924. In 1927, the tentative standard was approved as standard D198–27.

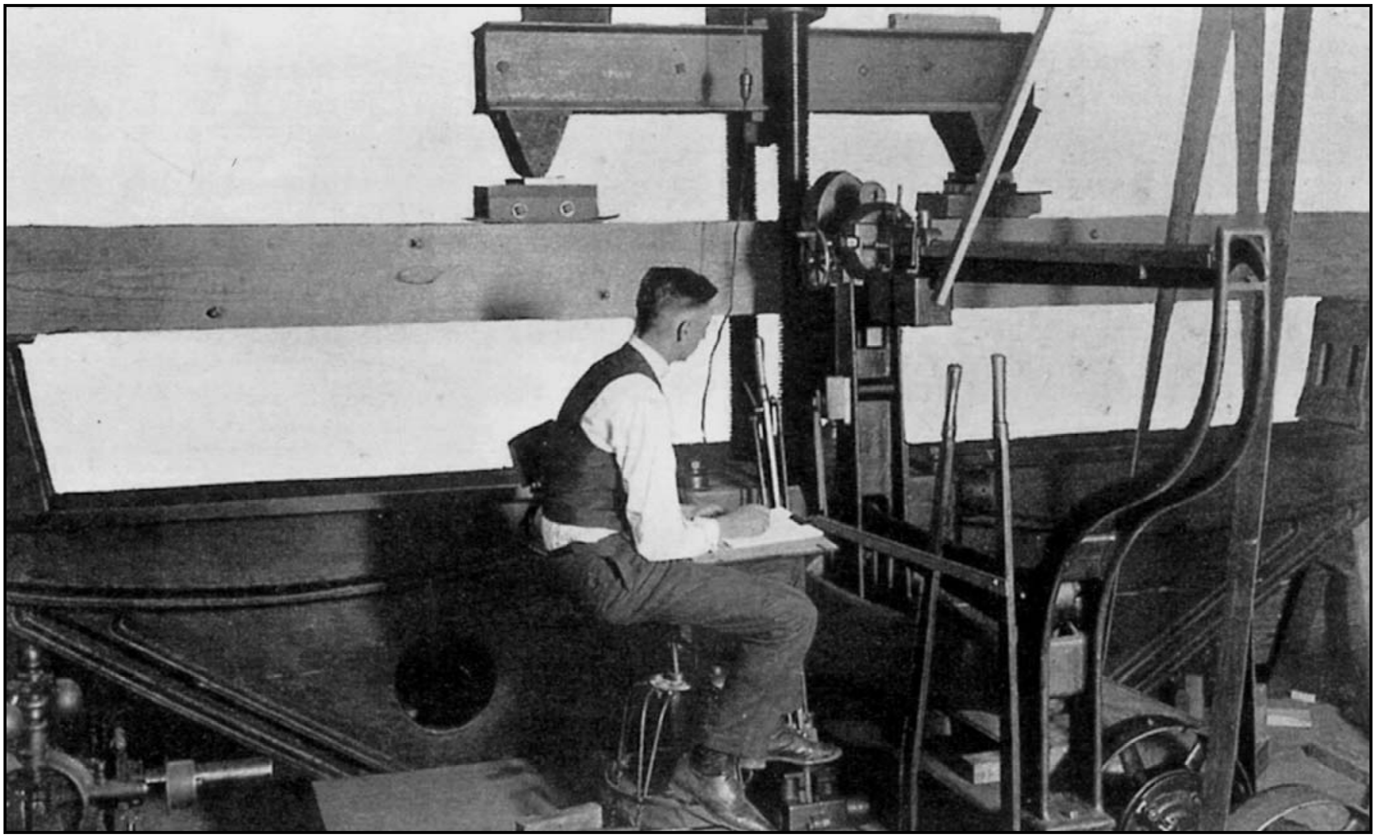


Figure 3—Testing of lumber at Forest Products Laboratory, around 1915.

World War I also brought attention to the need to standardize lumber grades, sizes, moisture content, and nomenclature (Shelley 1992). In 1922, the American Lumber Congress passed a resolution that a committee meet with Secretary of Agriculture Herbert Hoover to discuss standards and related matters. Their efforts resulted in the establishment of the Central Committee on Lumber Standards (predecessor to the American Lumber Standard Committee) by the Department of Commerce in 1922. In 1924, the Committee issued Simplified Practice Recommendation No. 16, the first national standard for lumber sizes and grades. This standard dealt primarily with nomenclature and grade descriptions. It did not deal with allowable design properties for lumber.

Scope

The history of standardized moisture content adjustment procedures is presented for the six mechanical properties for which allowable properties are currently assigned: flexural strength (modulus of rupture, MOR) and flexural modulus of elasticity (MOE), ultimate tensile stress (UTS) parallel to grain, ultimate compressive stress parallel to grain (UCS), ultimate compressive stress perpendicular to grain, and shear strength parallel to grain. Recommendations are provided for improving the consistency of adjustment procedures between different standards.

Modulus of Rupture

Early investigators understood that lumber was primarily used structurally in bending or in compression parallel to grain. They viewed strength in bending as more important than compression parallel to grain because failure in bending is likely to be catastrophic. Therefore, the amount of research effort placed on bending studies far outweighs that for other stress modes.

Development of Fundamental Concepts

Forest Service Bulletin 10 (Roth and Fernow 1895) provides a discussion of the influence of weight and moisture content on the strength of clear wood, but provides little information not previously known. In his pioneering research at the Yale laboratory on how moisture content affects the properties of small clear specimens, Tiemann (1906) established the concept of a fiber saturation point—the moisture content at which the cell walls are completely saturated with (bound) water, but no (free) water exists in the cell lumen. He also established that only those changes in moisture content that occur below the fiber saturation point affect properties. Although these concepts were vital to the implementation of moisture content–property adjustment procedures for lumber, the clear wood property increases established by Tiemann were never proposed for adjusting the properties of large members containing defects.

Table 2—Ratio of average mechanical properties for full-size, air-seasoned timbers to those of green timbers[a]

Species	MOR	MOE	Horizontal shear	Compression parallel to grain	Compression perpendicular to grain
Douglas-fir	1.06	1.02	1.33	1.22	1.12
Western larch	1.18	1.14	1.18	1.64	1.31
Longleaf pine	0.94	1.16	0.77	1.00	1.01
Shortleaf pine	1.19	1.17	1.10	1.76	2.26
Loblolly pine	1.19	1.07	1.30	1.46	1.31
Western hemlock	1.21	1.20	1.07	1.73	1.09
Tamarack	1.21	1.10	1.15	1.34	—
Norway pine	1.57	0.25	1.20	1.66	—
Redwood	0.87	0.85	—	1.16	1.21

[a] Adapted from Cline and Heim 1912. MOR is modulus of rupture; MOE, modulus of elasticity.

Moisture content was also included as a variable in the full-size testing program of the Forest Service that was summarized in Bulletin 108 (Cline and Heim 1912). Using data for beams tested in bending and in compression parallel and perpendicular to grain (Table 2), the researchers concluded that although seasoning results in a significant increase in strength for small clear specimens, for timbers the increase in bending strength resulting from drying may be offset by a weakening of the timber, which is caused by the formation of splits (see Apps. B, H). Grading rules for structural timbers proposed by the Forest Service in 1915 show no allowable increase in strength properties as a result of seasoning (Betts 1915). This is consistent with the 1895 recommendations for railway structures (Berg and others 1907).

A system of grading lumber much like that currently in use is described in USDA Circular 295 (Newlin and Johnson 1923). Grade descriptions were developed for four grades using the test results summarized in Bulletin 108.[1] The grades were designated S1, S2, S3, and S4, which were later associated with Extra Select, Select Structural, Standard, and Common, respectively. The minimum strength ratios of S1, S2, S3, and S4 were limited to, respectively, 88%, 75%, 62%, and 50% that of clear wood. In Circular 295, allowable properties (called "working" properties) for these grades are for all widths of timbers, with no special rules for lumber 4 in. and less in thickness (hereafter referred to as ≤4 in. lumber). No specific rules for seasoning adjustments are given in Circular 295. However, working stresses are

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[1] The green and dry timbers tested were not necessarily of equal quality. The data in Bulletin 108 were used to develop the visual grading system that we now use to describe "quality," and thus these were ungraded timbers by current definition. See Appendix B for other early data on the effect of moisture content on timber properties.

Table 3—Early versions of working stresses in bending for Select (S2) grade of spruce

	Extreme fiber stress (lb/in^2) for different exposure conditions							
	Continuously dry		Occasionally wet		Continuously wet			
Publication and spruce species	Timber	Joist & plank	Timber	Joist & plank	Timber	Joist & plank	Horizontal shear (lb/in^2)	Modulus of elasticity ($\times 10^3$ lb/in^2)
Circular 295								
Red, white, Sitka	1,100	—	900	—	800	—	85	1,200
Engelmann	750	—	650	—	500	—	70	800
Newlin and Johnson 1924								
Red, white, Sitka	1,100	1,280	900	—	800	—	85	1,200
Engelmann	750	880	650	—	500	—	70	800
ASTM D245–27								
Red, white, Sitka	1,100	—	900	800	800	710	85	1,200
Engelmann	750	—	—	580	—	440	70	800

presented for three different moisture conditions (shown in Table 3 for bending):

> **Continuously dry**—“Continuously dry” refers to use in interior or protected construction not subject to conditions of excessive dampness or high humidity.
>
> **Occasionally wet**—“Occasionally wet but quickly dried” assumes use in such exterior structures as bridges, trestles, grandstands or bleachers, and exposed framework of open sheds.
>
> **Continuously wet**—“More or less continuously damp or wet” applies to material exposed to waves or tidewater, placed in contact with earth, or used in building components that are more or less continuously exposed to water.

John A. Newlin

The values for modulus of rupture (MOR), compression parallel to grain, and compression perpendicular to grain vary by exposure condition; the values for horizontal shear (as determined from bending specimens) and modulus of elasticity (MOE) do not. It would be easy to assume that these were property decreases for increases in moisture content. However, this is not the case. The clearest example of the calculation of allowable properties in this period was given in a paper presented by John A. Newlin (1927) to the American Society of Civil Engineers in 1925. Newlin calculated a “safe stress for a Select (S2) grade of spruce structural timber” as

$$5{,}760(3/4)(3/4)(9/16) = 1{,}820 \text{ lb/in}^2$$

Newlin stated that

> the starting point would be 5,760 lb/in^2, which would be the average modulus of rupture of small, clear stock tested green at standard speed. Reduce this by one-fourth to take care of variability of the clear wood; make another reduction of one-fourth to take care of the maximum defect permitted in the grade; then take off about seven-sixteenths for the dead load effect over a number of years (elsewhere stated as a 10-year load duration).[2] (Newlin 1927)

Newlin said that this is the “stress under long-term loading at which an occasional timber, possibly 1 in 25, would be expected to fail” and notes that “the recommended stress of 1,100 lb/in^2 gives a factor of safety of 5/3 for this bad timber and this worst loading condition (1,820 × 3/5 = 1,100).” The value of 1,100 lb/in^2 is the value listed in Circular 295 for Sitka spruce for S2 grade used under shelter in dry locations (Table 3). Thus, the working stress for the continuously dry exposure is based on test results for green specimens.

In an unpublished memorandum, Newlin and Johnson (1924) discussed the factors involved in determining the working stresses given in Circular 295. They noted that “timber in wet or damp locations is subject to deterioration from decay. Under such conditions lower stresses have been recommended in order to avoid too frequent renewals.”

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[2] Note that a reduction of 7/16 means that 9/16 remains.

Robert P. Johnson

Thus, the different allowable properties at three exposure conditions are really a response to decay hazard and are not indicative of the effect of moisture content on strength. The reasoning for the amount of the reductions is not stated.

After reviewing all the data collected at Forest Products Laboratory to date on flexural strength of green and dry full-size lumber, Newlin and Johnson (1924) did recommend some increase in flexural strength with seasoning for lumber ≤4 in. thick (which they called Joist and Plank). The memorandum stated that the authors had observed "an increase of about 20% for S1, 15% for S2, 8% for S3, but no increase for the S4 grade." The appendix to the memorandum includes the following statement (under Modifications of and Additions to Circular 295 developed in conference with Forest Products Laboratory):

> The working stresses for dimension (lumber) not thicker than 4 in. may be increased proportionally over those for timbers in dry locations with corresponding defects from equal stresses in a grade having one-half the strength of clear wood to stresses 25% greater than in timbers in a grade of clear wood strength. (Newlin and Johnson 1924)

For green lumber with a strength ratio of 50% or more, this rule can be written as:

$$SR_{dry} = SR_{green} + (SR_{green} - 50)/2 \qquad (1)$$

where SR is strength ratio (%).

Newlin and Johnson's memorandum clearly shows that for dry joist and plank, this is an increase for decreasing moisture content (Table 4). Although slightly more conservative than the increases cited by the authors in the main text of Circular 295 (Newlin and Johnson 1923), this "25% rule" closely approximates the experimental results reproduced in Table 4.

Table 4—Results of FPL tests on effect of moisture content on MOR of ≤4-in.-thick lumber[a]

Grade	Minimum strength ratio, green condition	Increase in strength for dry location	
		Experimental evidence	25% rule
S1 (Extra Select)	88	20	22
S2 (Select)	75	15	17
S3 (Standard)	62	8	10
S4 (Common)	50	0	0

[a]Adapted from Newlin and Johnson (1924).

Circular 296, *Standard Grading Specifications for Yard Lumber*, was also published at this time (Ivory and others 1923). This publication contained recommendations on lumber sizes and adjustments to size for changes in moisture content. At this time, there were no recommended design values for dimension (yard) lumber. Yard lumber was recommended for framing uses such as residential housing, which was not considered a structural use requiring design values (Shelley 1992).

ASTM D245

The Formative Years

The development of ASTM D245 is chronicled in Appendix C. ASTM D245, Standard Methods for Establishing Structural Grades for Visually Graded Lumber, was established as a tentative standard in 1926 and as a full standard in 1927 to "offer a means of selecting structural material for strength" and "that appropriate working stresses may be assigned for its use." The appendix of D245–26T (ASTM Proceedings 1926) gives the same working stresses for timbers, for the three exposure conditions, given in Circular 295 (Table 3). However, the special increases proposed in the unpublished memorandum for pieces ≤4 in. thick and used continuously dry are not included. Instead, only the allowable property for green timbers is listed for the continuously dry exposure condition. Rather than allow a higher allowable property for dry dimension lumber (≤4 in. thick) used in a dry location, D245–26T lists lower allowable properties for occasionally wet and continuously wet hazard conditions.

To this point, the seminal work of Newlin and Johnson clearly provided the basis for the early versions of D245. From their unpublished memorandum (Newlin and Johnson 1924), it is clear that these authors intended allowable properties for members >4 in. thick to be based on the properties of green wood. However, they also recognized an increase in allowable bending strength for ≤4-in.-thick lumber that was used continuously dry. Moreover, it is clear that they intended the properties of lumber of all widths to be reduced for expected decay hazards if not used in a continuously dry environment. Table 3 is an attempt to show the evolution of these concepts in a clear manner. The actual format, terminology, and, sometimes, the allowable properties themselves also evolved over time. Appendix D gives the properties of S2 grade lumber as originally presented in three "foundation documents:" Circular 295, Newlin and Johnson's unpublished memorandum, and ASTM D245–27.

The next revision of ASTM D245 occurred in 1930. With only editorial changes, the 25% rule discussed in the appendix of the unpublished memorandum by Newlin and Johnson (1924) is included in the 1930 revision and repeated in the 1933 revision:

> In dimension sizes 4 in. and less in thickness…and in these sizes used in dry locations, working stresses in extreme fiber in bending are increased proportionately from equal values with timbers, and dimension not continuously dry, in a grade having 50% of the strength of clear wood, to values 25% greater in clear wood. (Newlin and Johnson 1924)

With the 1936 revision of D245 (D245–36T, ASTM Proceedings 1936), the format of the standard changed dramatically. Much discussion of the derivation of properties was dropped. Included in the text were grade descriptions, but only those "recommended by the Forest Products Laboratory." The appendix included standard stress grades and working stresses. The appendix stated that "the detailed reasoning basic to these grades will be found by a report of the U.S. Forest Products Laboratory…Miscellaneous Publication 185" (Wilson 1934). It also stated that "reference should also be made to the 'Working Stresses' appearing in the appendix of…D245–33."

The revised standard was very brief, primarily a collection of grading rules. The format was maintained in D245–37 and until the next revision (D245–49T), which did not occur until the end of World War II. The adoption of the reference to Miscellaneous Publication 185 (Misc. Pub 185) complicates tracking the dates when a "modification" was made to D245. As will be seen, two revisions (supplements) to Misc. Pub. 185 were made before a new version of D245 was issued. We assume that because Misc. Pub. 185 is referenced in D245–37, any subsequent changes to Misc. Pub. 185 were directly incorporated into D245, even without a new edition of that standard.

Attempts Toward a Comprehensive Document

Miscellaneous Publication 185 (Wilson 1934) was an attempt to provide a comprehensive document on structural grading. According to this publication, Circular 295 (Newlin and Johnson 1923) presented the principles of grading for strength, but it did not show how to determine appropriate working stresses. With respect to seasoning, Wilson noted that although drying greatly increases the strength of wood fibers, "in large timbers this increase is largely offset by the checking that occurs in seasoning."

T.R.C. Wilson

He concluded the following:

> The minimum strengths in any group of large pieces are increased so little by seasoning that beams and stringers and posts and timbers (except pieces 4 by 4 in.) are given no higher working stresses for continuously dry than for continuously wet service. The increase in strength of pieces 4 in. and less in thickness with seasoning is sufficiently great, and is uniform enough, that it is given recognition in working stresses for material that will be continuously dry in service. (Wilson 1934)

For lumber ≤4 in. thick, the 25% rule discussed previously is restated. For continuously dry use, Misc. Pub. 185 gives working stresses for various lumber association grades.

With reference to Circular 295, Wilson stated that

> the tables previously published by the Forest Products Laboratory included values for three types of exposure. Ratios among stresses for the different exposure conditions as given in these tables varied somewhat with species but averaged approximately as… (Wilson 1934)

The average ratios among stresses for different exposures in Circular 295 are given in Table 5. The discussion again makes clear that lower stresses for lumber not used continuously dry were responses to decay hazard, not reduction in strength resulting from increased moisture content. These decay hazard classes are also clearly presented in the 1935 edition of the *Wood Handbook* (FPL 1935). However, how the reductions for decay hazard were originally determined is not discussed.

A supplement to Misc. Pub. 185, issued in 1940 (Wilson 1940), extended the concept of strength ratios to grades with strength ratios below 50%; for ≤4-in.-thick lumber, restrictions on knots and slope of grain were extended to the full length of the piece. This supplement also introduced restrictions on moisture content for specifications based on

Table 5—Average ratio among stresses for different decay hazard exposures in Circular 295[a]

	Stress ratio (%) for various types of exposure		
Type of stress	Continuously dry or submerged	Continuously wet, but quickly dried	More or less continuously damp or wet
Stress in extreme fiber in bending	100	85	71
Stress in compression perpendicular to grain	100	70	58
Stress in compression parallel to grain	100	92	78
Stress in horizontal shear	100	100	100
Modulus of elasticity	100	100	100

[a] Wilson 1934.

satisfactory performance (as opposed to property increases) for lumber to be used for house framing. For such material, the supplement stated that “material shall be seasoned to a moisture content of not to exceed 19% in any individual piece.” The intent was clarified in a footnote: “Since seasoning to an average moisture content well below 19% is desirable for house-framing material, this figure should be regarded as a maximum, subject to revision downward as increased drying facilities become available.”

A second supplement to Misc. Pub. 185 was issued in 1948 (FPL 1948). The purpose of this supplement was to document conclusions on working stresses drawn from favorable performance of wooden structures constructed during World War II, when certain restrictions on wooden buildings had been relaxed. No changes in moisture adjustments for MOR were made in this supplement, but some changes were made in other properties, which will be discussed in subsequent sections of this report.

Extending the 25% Rule

The basic idea expressed by the 25% rule that the effect of moisture content on the bending strength of lumber ≤4 in. thick was somehow dependent upon the quality (or strength) of the lumber was retained in ASTM D245 from 1930 through 1968. However, the interpretation of how this adjustment could be applied began to change. According to ASTM D245–49T, “in these sizes used in dry locations, higher working stresses in extreme fiber in bending can be permitted with the same size defects as in pieces of larger size, or greater defects can be permitted with the same working stress” (D245–49T, table X, footnote a). The standard further stated that the increase in strength caused by seasoning is “commonly taken into account by increasing the strength ratio by half its excess over 50%.” In addition, when one takes “advantage of the increase in strength from drying by increasing permissible sizes of knots or other characteristics rather than by increasing the working stress…the working stress may have to be reduced if the material is to be used under wet conditions.” This interpretation is much more complex than the original principles given by Newlin and Johnson (1923) and was therefore more difficult to implement in practice. Footnote b of table X in D245–49T states that “modification for seasoning in current commercial practice is accomplished by liberalizing defects in grade rather than increasing working stresses.”

By the early 1950s, there was an increasing trend to market 2-in.-thick lumber separately from lumber of other thicknesses. It therefore appeared logical to question whether the 25% rule developed for lumber 2 to 4 in. thick could be liberalized for 1-in.-thick lumber. After a review of published U.S. data and then unpublished Canadian data (later presented in Jessome (1971)) for 1- and 2-in-thick lumber, Wood (1953) concluded that stresses for green material with a strength ratio of 50% or more could be increased by 25% if used under continuously dry conditions. This adjustment was judged to be “conservative enough” for most species. The increase of 25% in the allowable bending strength of 1-in.-thick boards was recommended in the 1955 edition of the *Wood Handbook* for all grades and adopted in ASTM D245–57T for lumber 1 or 2 in. in thickness. This across-the-board 25% increase was not, strictly speaking, an extension of the 25% rule.

By the mid-1950s, some Southern Pine manufacturers produced a class of lumber with 15% maximum moisture content. Western producers and others were drying lumber to the 19% maximum moisture content specified in Misc. Pub. 185 (Wilson 1940). Thus, ASTM D245–57T retained the statement of D245–49T for lumber 2 to 4 in. thick, but it noted that “working stresses for all grades of 1 or 2 in. lumber dressed at 15% or lower moisture content and is fabricated and used under conditions where that moisture content is not exceeded may be increased…by one-quarter in bending.” That is, working stresses may be increased over the values for already-dry lumber at 19% maximum moisture content.

This increase in working stresses did not depend upon the grade (strength ratio) of the lumber. The 25% grade-independent increase was not taken in addition to the 25% rule increase, but rather in place of it. Thus, a 1-in.-thick board could take the grade-independent 25% increase and a 2-in.-thick board could take either the 25% rule increase (the magnitude of which depended upon grade) or the grade-independent 25% increase. Note that the implementation of a property increase for dry material was becoming even more complex. ASTM D245–57T also retained the option for liberalizing grade characteristics given in D245–49T.

In the early 1940s it became clear that it would be necessary to establish standard widths and thicknesses for both green and dry lumber sold under the American Lumber Standard system and to tie the standard dry sizes to a specific moisture content (Wood 1964). However, reaching a consensus on this standardization proved exceedingly difficult and agreement was not reached until 1963. The agreement based dry sizes for 2-in.-thick dimension lumber and boards on a maximum moisture content of 19%, with dry width and thickness based on shrinkage to an average moisture content of 15%. This consensus agreement helped spur the 1964 revision of D245.

ASTM D245–64T retained both the 25% rule from D245–57–T for 2- to 4-in.-thick lumber and the grade-independent 25% increase from D245–57T for 1- to 2-in.-thick lumber surfaced and used at ≤15% moisture content. However, a 15% increase in working (allowable) stresses was added for 1- to 2-in.-thick lumber with moisture content of not more than 19% at time of manufacture and that was used in dry conditions. The option for liberalizing grade characteristics instead of increasing allowable properties was also retained.

With these changes, the moisture adjustment procedures for bending strength in ASTM D245 reached their maximum complexity.

Changes After 1965

The late 1960s were another period of major transition for ASTM standards for assigning lumber properties. During this time, a major public–private research and development effort focused on obtaining new, independent estimates of mechanical properties for clear wood (FPL 1965, Wahlgren and others 1975). Emphasis was on the major species of Southern Pine, Douglas-fir, western hemlock, and certain true firs. Solid-sawn lumber and plywood were both key interests. The strategy involved systematically studying the geographic variation in properties, using the more easily measured specific gravity as the indicator of mechanical properties. The result of this effort was a new standard, ASTM D2555, which included tables of clear wood properties for green wood by individual species, obtained from the new density studies or from the procedures of ASTM D143. Ratios of dry to green properties were also calculated and included in D2555. The new standard was intended to provide a starting point for applying ASTM D245.

To make ASTM D2555 and D245 work systematically in tandem, it was necessary to address numerous anomalies. As the history of standards development has indicated, many early procedures for assigning properties involved judgments, often based on limited data. In the procedures proposed in Circular 295, and later adopted in D245–26T, judgment factors (sometimes referred to as Newlin factors) were sometimes applied to individual species because the properties of the species were judged to be more or less variable than those of the average species. For some species, the basic clear wood stresses were sometimes reduced because of drying behavior that Newlin had observed in the laboratory. Thus, there was an effort to revise D245 to treat all species by a common set of well-defined decision rules (Robert Ethington, personal communication).

The 1960s were also a time of fairly intense testing of full-size lumber, for the first time since the early studies of Cline and Heim (1912). These more contemporary studies were based entirely on 2-in.-thick lumber (Doyle and Markwardt 1966, 1967; Doyle 1968), and they generally showed higher strength values than those calculated from D245 procedures. At the time, the ASTM task group attributed much of the higher strength values to drying effects greater than those traditionally assumed (Robert Ethington, personal communication).

The 1969 revision of D245 contained neither of the two provisions for increasing the bending strength by 25% for dry lumber (25% rule for 2- to 4-in.-thick lumber or grade-independent 25% increase for 1- or 2-in.-thick lumber). However, the concept of two maximum moisture content levels, 15% and 19%, was clearly identified. For bending of dimension lumber, the increases were 35% and 25%, respectively, provided that the proper allowances were made for shrinkage (Table 6). D245–69 explicitly assumes that lots (batches) of lumber dried to a maximum moisture content 19% have an average moisture content of 15%, and lots of lumber having a maximum moisture content of 15% have an average moisture content of 12%. Adjustments of properties were traditionally adjusted to the average moisture content of the group, rather than the maximum.

Table 6—Modification of allowable unit stresses for seasoning effects for ≤4-in-thick lumber in D245–69

	Increase (%) in allowable stress and MOE for different maximum moisture contents[a]	
Property	19%	15%
Extreme fiber in bending	25	35
Tension parallel to grain	25	35
Horizontal shear	8	13
Compression perpendicular to grain[b]	50	50
Compression parallel to grain	50	75
Modulus of elasticity	14	20

[a] Above that of green lumber properties, the increase for 15% maximum moisture content shall not exceed ratio of dry to green clear wood strength shown in Ratios of Dry to Green Clear Wood Properties in D2555. Where ratios in D2555 are less than those shown in this table, proportionate reductions shall be made for lumber at 19% maximum moisture content.

[b] Increase in compression perpendicular to grain is the same for all degrees of seasoning below fiber saturation because outer fibers that season rapidly have the greatest effect on this strength property regardless of extent of seasoning of inner fibers.

The new adjustment factors for 19% and 15% maximum moisture content were qualified by the addition of the statement that “the increases in allowable properties given…at 15% maximum moisture content shall not exceed the ratio of dry to green clear wood strength shown in…D2555” (App. E). This statement is apparently the introduction of dry-green moisture ratios for small clear specimens as a limiting factor for adjusting lumber strength. For certain properties of a few species, concern was expressed about cases in which the increase for drying lumber (25% and 35% increases of D245) would exceed that measured on small clear specimens, a situation considered to be indefensible. For most species, the clear wood dry-green ratios exceed the adjustment based on experimental results with lumber. The D245–69 adjustment procedures have been maintained through the current edition (D245–99).

ASTM D2555

ASTM D2555, Standard Methods for Establishing Clear Wood Strength Values, was approved in 1966 as a tentative standard to provide an “authoritative compilation of clear wood strength values for commercially important species.” However, the edition of D245 in effect that year, D245–64T, still provided the traditional “basic stresses.” When D2555 was accepted as a full standard in 1969, D245–69 referenced D2555–69 for clear wood stresses (called unit stresses). The 1969 version of D2555 also contained, for the first time, the dry-green ratios by species for the properties that were included in D245. During the 1970s, the Forest Products Laboratory conducted clear wood studies of 10 eastern and western softwood species (Bendtsen 1970, 1972, 1973, 1974) using a random procedure for selection of trees. These studies used an equal number of green and dry observations per property. The new dry-green ratios for the study species were incorporated into D2555 in the 1988 revision (App. E) and remain the values listed in the current edition (D2555–98).

ASTM D2555–67T also marked the introduction of the concept of calculating a clear wood “5th percentile” for derivation of allowable properties. The 1955 edition of the *Wood Handbook* introduced coefficients of variation, by property, for green clear specimens. D245–67T built on this concept to account for the variance of strength within a species or species group. Historically, Newlin had accounted for within-species variability of bending strength by multiplying the clear wood mean value by a factor of 0.75. This is approximately the 5th percentile for most species, assuming a normal distribution for clear wood strength properties and a coefficient of variation for MOR of 16%. With the exception of moisture content adjustments using the 25% rule, most adjustment factors had historically been applied to mean trends or had been applied as constant percentage adjustments (per the 25% and 35% moisture content adjustment factors in D245–69T). As will be discussed in the section on ASTM D1990, this explicit assumption of a lower tail property eventually led to questioning the application of moisture content adjustment factors without regard to quality level (grade).

ASTM D2915

ASTM D2915, Standard Methods for Evaluating Allowable Properties for Grades of Structural Lumber, was approved as a tentative standard in 1970 and as a full standard in 1974. This standard was established for “assessing the appropriateness of the assigned properties, and thus for occasionally checking the effectiveness of grading procedures.” The introduction to D2915 stated that

> when making an evaluation of the entire marketed production of a grade, it is intended that this method will supply…a high degree of confidence. It may also be used for less broad purposes, for example, to evaluate the properties of individual lots of lumber, or the output of a single grading machine. For situations where repeated sampling is likely to take place, or the lot size is small, this method is not particularly efficient. (ASTM D2915)

For the first time in the history of Committee D7, this new standard provided guidelines for independent establishment of allowable properties based on testing lumber. One of the first applications of D2915 was in calculating allowable properties for Machine Stress Rated lumber. The standard states that “properties shall be adjusted to a single moisture content appropriate for the objectives of the testing program...” and provides the following adjustment formula:

$$P_2 = P_1\left[\left(\ \ - \ \ M_2\right)/\left(\ \ - \ \ M_1\right)\right] \tag{2}$$

where P_1 is property measured at moisture content M_1, P_2 is property predicted at moisture content M_2, M_1 and M_2 are

coefficients (Table 7).

The standard states that the equation “yields adjustments consistent with the moisture factors given in…D245.” It also suggested that “adjustments for more than five percentage points of moisture content are to be avoided.”

The original intent of the moisture adjustment procedure was apparently to have a standard for deriving properties of dry lumber, with no intent of using it to adjust these properties to a green moisture content level (Robert Ethington, personal communication). It was also felt that for relatively small changes in moisture content, a straight line would adequately describe property changes around the 12% to 15% expected target levels (Robert Ethington, personal communication). With this philosophy, Equation (2) predicts no change in allowable compressive stress perpendicular to grain. This is consistent with the D245 assumption that perpendicular-to-grain compressive strength is increased 50% in going from green to dry, regardless of the actual dry moisture content (that is, no change in compression perpendicular to grain in going from one dry level to another).

In the years following the adoption of D2915–70T, there developed within Committee D7 a concern that obtaining the precise increases for drying recommended in D245 would require implied maximum values of M_1 that varied with property (Table 7). In 1984, D2915 was modified with an explicit statement that “moisture contents M_1 greater than 22% are taken as 22%” and that “M_2 must be less than or equal to 22%.” This change remains in effect in the current version of D2915 (D2915–98).

The introduction of the 22% maximum value for M_1 implies a major change in the intent of the use of Equation (2). Despite the “suggestion” that adjustments for changes in moisture content be held to less than a 5% moisture content adjustment, the implication is that it is all right to use Equation (2) to adjust to a green property level. Using the

Table 7—ASTM D2915 moisture content adjustment procedures for ≤4-in.-thick lumber[a]

	Coefficients of $P_2 = P_1$ − M_2 − M_1)]				Increase (%) in allowable property above that of green lumber for two average moisture content levels[b]			
			Max value of M_1		15%		12%	
Property			1970T[c]	1984	D245–99	D2915–98	D245–99	D2915–98
Modulus of rupture	1.75	0.0333	22.5	22	25	22.9	35	32.7
Modulus of elasticity	1.44	0.0200	22.0	22	14	14.0	20	20.0
Tensile strength	1.75	0.0333	22.5	22	25	22.9	35	32.7
Compression parallel to grain	2.75	0.0833	21.0	22	50	63.6	75	90.8
Shear strength	1.33	0.0167	19.8	22	8	12.1	13	17.3
Compression perpendicular to grain	1.00	0	NR	NR	50	0	50	0

[a] P_1 is property measured at moisture content M_1; P_2, property predicted at moisture content M_2; M_1 and M_2, moisture contents (%); an

[b] Assumes maximum value of M_1 is 22% moisture content in D2915–98.

[c] Implied maximum value of M_1 to obtain D245 adjustments. Implications of adjusting from green values not valid by intent of task force in 1970 (see text).

22% maximum value, current versions of D245 and D2915 are therefore implied to have major differences for some properties when adjusting from green to an average moisture content of either 15% or 12%, and the recommendations on adjustments for compressive strength perpendicular to grain would appear totally inconsistent (Table 7). It may be appropriate to reconsider the intent of D2915 and resolve apparent differences with D245 and D1990.

ASTM D1990

ASTM D1990, Standard Methods for Establishing Allowable Properties for Visually Graded Dimension Lumber From In-Grade Tests of Full-Size Specimens, was established in 1991. This standard provides guidelines for sampling, testing, and deriving allowable properties for large lumber populations. D1990 is intended to be consistent in philosophy with D2915, but it is applicable only to visually graded lumber and is therefore more prescriptive than D2915. Unlike D2915, methods are also given for estimating allowable properties for untested grade–size combinations and for calculating allowable properties for species groups.

ASTM D1990 evolved from the joint U.S.–Canadian In-Grade testing program. An overview of this program was presented at an ASTM workshop in 1988 (Green and others 1989). Because some lumber sampled in the In-Grade program was to be tested in the field using portable equipment, it was recognized that equations to adjust properties for change in moisture content would be critical to the conclusions.

In 1979, the existing standardized procedures were reviewed and a work plan was formulated to develop new procedures (Green 1980). This resulted in two studies being conducted in virtually identical fashion (McLain and others 1984, Aplin and others 1986). In each study, green 2-in.-thick lumber in three commercial grades was obtained from one mill (Green and Evans 1989). Each grade of lumber was divided into four samples of about 120 specimens; three samples were equilibrated to 10%, 15%, and 20% moisture content and the fourth sample was tested green. The specimens were tested on edge in one-third-point bending using a span-to-depth ratio of 17:1.

As had been assumed by the 25% rule, results of these studies showed that change in strength with change of moisture content is a function of lumber quality. Higher quality (strength) lumber is more sensitive to change in moisture content than is lower quality lumber (Fig. 2). The studies also showed that strength does not necessarily increase with decreasing moisture content.

Numerous analytical models, including models based on ASTM D245 and D2915 principles, were compared to determine how close the corresponding percentiles of the four moisture content distributions were to each other after adjustment to a common moisture content. As in the research conducted by Wilson (1932), the intersection moisture content, M_p, for each model type was determined analytically using a curve fitting technique.[3] The resulting “best” model types in terms of versatility and accuracy for MOR were quadratic surface models (Green and others 1986, 1988). The model chosen to adjust data in the In-Grade program was a quadratic surface model with an assumed M_p value (called “assumed green value” in D1990) of 23% (Evans

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[3] M_p is defined as the moisture content at the intersection of a horizontal line representing the strength of green wood and an inclined line representing the strength of dry wood.

and others 1990, Green and Evans 1989, Green and Evans 1992).

The development of ASTM D1990 moisture adjustment procedures began with the methodology used in the In-Grade program. However, concern was raised about the complexity of using the model since it required finding the roots of a cubic equation (Evans and others 1990). Compromises, such as stipulating the use of “an appropriate adjustment procedure” rather than naming a specific adjustment model or using the model in D2915, were also unacceptable to many.

The D1990 task group proposed a simplified version of a linear surface model that was accepted by Committee D7. The form of the model is

$$P_2 = P_1 \qquad \text{if MOR} \le 2{,}415\ \text{lb/in}^2$$
$$P_2 = P_1 + \left\{\frac{P_1 - 2{,}415}{40 - M_1}\right\}(M_1 - M_2) \qquad \text{if MOR} > 2{,}415\ \text{lb/in}^2 \tag{3}$$

where P_1 is property measured at moisture content M_1, P_2 is property predicted at moisture content M_2, and M_1 and M_2 are moisture contents (%).

This adjustment equation was “assumed valid for moisture contents between 10% and 23% (assumed green value).” The rationale for this decision began by noting that the linear surface models fit to the data were almost as good as the quadratic surface model (Table 8). Here, the smaller the average maximum absolute difference between the model and data at a given percentile level the better the fit of that model.

In a note to the D1990 task group, Green and Evans developed a simplified version of the linear model; the major elements of their original derivation are presented in Appendix F. A lower limit of 10% moisture content was chosen because this is the lowest moisture content tested in the studies that formed the basis for the models (Green and Evans 1989). Limiting the adjustments to moisture content above 10% also avoided the regions where the quadratic surface model and the simplified model showed substantially different trends (Fig. 4). Equation (3) shows the lower limits of MOR below which the model assumes that no adjustment with change in moisture content is needed. Fitting the model on the upper end of the data was also of concern. If the data are too sparse, then the model might become too sensitive to a few data points. Generally, the 95th percentile of the highest grades was used to set upper limits, beyond which the predictive relationship between MOR and moisture content was forced to remain parallel to the last valid fitted line. For MOR, this upper limit is 9,600 lb/in^2 for green lumber.

Although seldom used in practice (Evans and others 2000), ASTM D1990 allows strength properties (MOR, ultimate tensile stress, ultimate compressive stress) of a species to be “normalized” relative to the properties of Douglas Fir and Southern Pine used to develop the moisture content adjustment models (Green and Evans 1989). The concern that led to this option was that the moisture content–strength models tended to flatten out and show no change in properties at low strength levels. Without some type of adjustment, a significant portion of the strength distribution of a much weaker species might be below this lower limit. Therefore, the concept was to “scale” the data for a lower strength species relative to that of Douglas Fir and Southern Pine. The equation is given in Appendix F.

Table 8—Moisture content adjustment models for MOR at 15% moisture content used to select adjustment model for D1990–91

		Average maximum absolute difference (lb/in^2) for mean and different percentiles					
Species	Model[a]	Mean	5th	25th	50th	75th	95th
Douglas Fir	No adjustment	2,277	727	1,662	2,201	3,182	4,075
	Quadratic surface	574	529	664	721	868	973
	Linear surface, linear	815	681	813	999	1,116	1,197
	Linear surface, quadratic	823	517	801	1,013	1,170	1,224
	Linear surface, cubic	826	455	804	1,013	1,187	1,209
	Simplified model	797	458	801	999	1,116	1,197
Southern Pine	No adjustment	2,593	1,073	1,663	2,586	3,698	4,788
	Quadratic surface	535	801	759	766	778	893
	Linear surface, linear	531	1,005	872	833	783	1,037
	Linear surface, quadratic	549	949	861	824	844	1,189
	Linear surface, cubic	534	945	875	850	839	1,069
	Simplified model	535	939	860	819	811	1,009

[a] All models were fit using both Douglas Fir and Southern Pine data and assuming the intersection moisture content to be 23%.

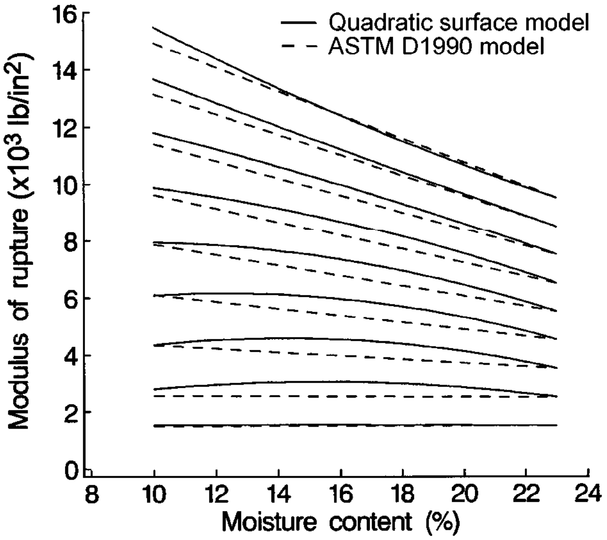

Figure 4—Effect of moisture content on bending strength of lumber as predicted by quadratic surface model and ASTM D1990 model.

As the preceding discussion indicates, D1990 procedures result in a larger increase in MOR when drying high quality lumber and less (or no) effect when drying low quality lumber. Thus, the basic idea that moisture effects on bending strength are somehow dependent on lumber quality, as first expressed in the 25% rule of Newlin and Johnson, was again confirmed. Moreover, although D1990 applies these factors only to 5th percentile levels, the research clearly shows that within a given grade, the higher the percentile level the larger the adjustment (Green and others 1986, 1988, 1990).

ASTM D1990 also contains “wet use” factors for adjusting allowable properties derived from the characteristic values at 15% moisture content using Equation (3) to green (Table 9). The allowable properties derived at 15% moisture content and the adjustment factors of Table 9 account for the normal shrinkage and swelling of lumber with changes in moisture content, as well as the changes in mechanical property values with change in moisture content. The basis of the adjustment factors is discussed in Appendix F.

Two other decisions that were made during deliberations about adopting D1990–91 are worthy of mention. The D1990 task group first discussed the application of adjustment procedures developed from tests of 2-in.-thick lumber to lumber 4 in. thick. A comparison of the results predicted for 2-in.-thick Southern Pine (Green and others 1986) with experimental results from 4-in.-thick Southern Pine (Gerhards 1968, 1970) does suggest that the MOR of 4-in.-thick lumber is slightly less sensitive to changes in moisture content than is the MOR of 2-in.-thick lumber. However, the studies by Gerhards were based on a very limited number of specimens. It was the task group’s opinion, confirmed by Committee D7, that the differences were not large and that to promote simplification of the standard it was appropriate to apply the new adjustment model to all 2- to 4-in.-thick lumber.

Table 9—Modification of allowable property values in ASTM D1990 when wood moisture content exceeds 19%

Property	Adjustment factor
$F_b \leq 1,150$ lb/in^2	1.0
$F_b > 1,150$ lb/in^2	0.85
F_t	1.0
$F_c \leq 750$ lb/in^2	1.0
$F_c > 750$ lb/in^2	0.8
MOE	0.9

The moisture content on which to base the “characteristic value” of D1990–91 was also a topic of discussion. A moisture content level of 15% was chosen because it seemed to represent the most common moisture content level for which lumber was produced across the United States. After D1990–91 was adopted, only the allowable properties at 15% moisture content were published in the grading manuals of the various rules-writing grading agencies and in the National Design Specifications (NDS) (AF&PA 1991). There was no indication from the research, or in ASTM discussions, that the properties at 15% maximum moisture content should be discontinued. Rather, this was a decision by the industry to simplify the presentation of properties in the NDS.

Modulus of Elasticity

ASTM D245

Early discussions did not recognize any increase in flexural modulus of elasticity (MOE) as a result of seasoning. In 1957, provisions were added to ASTM D245 (D245–57T) for a 10% increase in MOE for dry lumber of all grades of joist and plank and of timbers. For 1- and 2-in.-thick lumber that was planed and used at ≤15% moisture content, the allowable increase as a result of seasoning was also 10%. We could find no documentation as to exactly why the MOE adjustments were added in 1957. As discussed in the section on MOR, more highly engineered systems were beginning to be used, 2-in.-thick lumber was gaining in usage, and work was being conducted on shrinkage–moisture content relationships as part of the effort to standardize lumber dimensions throughout the United States (Wood 1964). Thus, perhaps there was a growing need to have a more precise MOE value for dry lumber. Certainly, the data available at the Forest Products Laboratory and elsewhere would have justified taking an increase in MOE for dry lumber (Jessome 1971, Wood 1953) (App. B).

In the 1964 revision of D245, an increase of 10% was still allowed for dry lumber of all thicknesses. For 1- and 2-in.-thick material dressed and used at a maximum moisture content of 15% or less, the allowable increase was raised to 20%. However, this factor was to be used in place of, not in addition to, the general 10% increase for all thicknesses. For 1- and 2-in.-thick lumber dressed and used at a maximum moisture content of 19%, an increase of 14% was allowed.

ASTM D245–69 extended the 20% increase for lumber manufactured and used at 15% and the 14% increase for lumber at 19% maximum moisture content to all lumber 4 in. or less in thickness (Table 6). The standard reduced the increase allowed for dry lumber of all widths in D245–67T to a 2% increase for lumber >4 in. thick based on net size at time of manufacture, providing the lumber was seasoned to a “substantial” depth before full load was applied. These are the moisture adjustment factors still given in the current edition of D245 (D245–98).

ASTM D2915

As previously discussed for MOR, D2915–70T made provisions for adjustments to MOE for changes in moisture content that were consistent with those of D245 (Eq. (2), Table 7). The explicit addition of 22% moisture content as a maximum value for M_1 in D2915–84 did not alter this comparison.

ASTM D1990

As discussed for MOR, moisture content adjustment procedures for MOE in ASTM D1990 were developed from studies on Douglas Fir and Southern Pine (McLain and others 1984; Aplin and others 1986; Green and others 1986, 1988; Green and Evans 1989). Unlike the strength models in D1990, the model for MOE developed as part of the In-Grade Program (Green and others 1989) was adopted directly into D1990–91. The model is a constant percentage adjustment model of the following form (Fig. 5):

$$P_2 = P_1\left[\frac{1.857-(0.0237M_2)}{1.857-(0.0237M_1)}\right] \tag{4}$$

where P_1 is property measured at moisture content M_1, P_2 is property predicted at moisture content M_2, and M_1 and M_2 are moisture contents (%).

This equation is assumed to be valid from 10% to 23% moisture content. The D1990 model predicts changes in MOE that generally agree with those of D245–98 (Fig. 5).

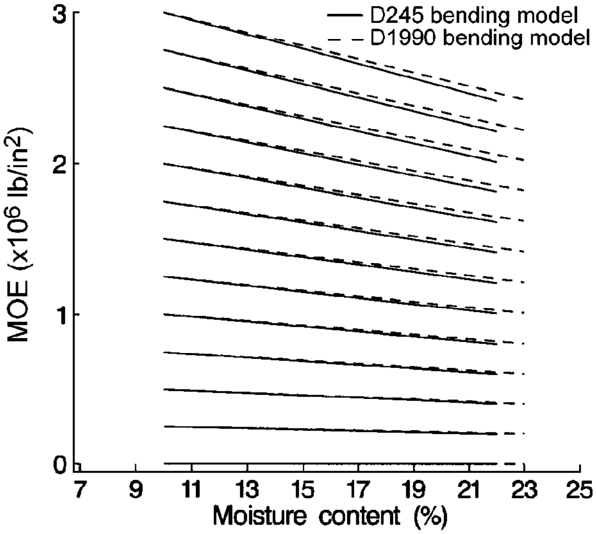

Figure 5—Effect of moisture content on modulus of elasticity of lumber in bending as predicted by the D1990 and ASTM D245 bending MOE models.

ASTM D1990 also contains “wet use” factors for adjusting allowable properties derived from the characteristic values at 15% moisture content using Equation (4) to green (Table 9). The allowable properties derived at 15% moisture content and the adjustment factors of Table 9 account for the normal shrinkage and swelling of lumber with changes in moisture content, as well as the changes in mechanical property values with change in moisture content. The basis of the adjustment factors (Table 9) is discussed in Appendix F.

Ultimate Compressive Stress Parallel to Grain

ASTM D245

As with MOR, ultimate compressive stress (UCS) parallel to grain increased with each of the three exposure conditions given in D245–26T. Like MOR, the compressive stresses were derived from green clear-wood mean values and were to be used without regard to the actual moisture content of the piece. These green values were listed for the continuously dry exposure condition and reduced for the occasionally wet and usually damp or wet condition to avoid too frequent removals because of possible decay hazard. These recommendations were not modified through D245–30.

As previously discussed in the section on MOR, D245–36T references Misc. Pub. 185 (Wilson 1934) for the development of working stresses. Without discussion, Misc. Pub. 185 states that for material ≤4 in. thick that is to be used under continuously dry conditions, the strength ratio for stress in compression parallel to grain is first increased by one-half its excess over 50%. Thus, the 25% rule is extended to parallel-to-grain compression for joist and plank.

According to ASTM D245–49T, studies had confirmed that increases in strength of timbers are largely offset by drying degrade. As in earlier versions of the standard, no increase in compression was allowed for timbers ≥ 4 in. thick; the standard again stated that the 25% rule was applicable to

2- to 4-in.-thick lumber stressed as short columns. Supplement 2 to Misc. Pub. 185 (FPL 1948) indicates that the increase is not applicable to long columns in the Euler class. Table IX of the standard also noted that for parallel-to-grain compression in joist and plank, "modifications in current commercial practice is accomplished by liberalizing defects in grade rather than by increasing working stresses."

ASTM D245–57T allowed a 10% increase for >4 in. thick lumber. For 2- to 4-in.-thick lumber, the 25% rule was retained, but an additional 10% increase could be taken. This latter increase was independent of grade. For 1- to 2-in.-thick lumber manufactured and used at a maximum moisture content of not more than 15%, D245–57T allowed working (allowable) stresses in compression parallel to grain to be increased 3/8 (37.5%) over stresses for green lumber. However, these increases were in place of, not in addition to, seasoning increases resulting from the 25% rule. The footnote to table IX of the standard was retained for parallel-to-grain compression of joist and plank, but stipulated that "modifications in seasoning in joist and plank may be accomplished either by liberalizing grade limitations or by increasing working stresses."

ASTM D245–64T retained the provisions of D245–57T but added an adjustment for 1- and 2-in.-thick lumber manufactured and used at a maximum moisture content of 19%. For compression parallel to grain, the increase over the green strength was 22%. Again, this increase was in place of, and not in addition to, other increases. The note on liberalizing grade limitations was retained.

The 10% increase for dry lumber ≥4 in. thick without regard to grade was continued in ASTM D245–69. For lumber ≤4 in. thick, D245–69 introduced the strength ratio independent factors still used in the current (2000) edition of D245 (Table 6). The drying factor at 15% maximum moisture content more than doubled, apparently because of the adoption of an average ratio based on clear wood. In addition, as noted in previous discussions of properties, for the first time these increases could not be more than the dry-green ratio from compression tests on clear wood specimens. These ratios were not available in D2555 until the 1970 version. Also, the note on liberalizing grade limitations in joist and plank was dropped from the standard.

ASTM D2915

ASTM D2915-70T was established to provide a method of assessing the appropriateness of assigned properties. As discussed in detail in the section on modulus of rupture, it was "suggested" in the standard that the moisture adjustment procedures reproduced in Equation (2) of this paper not be used for more than a 5% moisture content change. There was apparently no intent that this equation be used to adjust properties to (or from) green moisture content. However, the addition of a maximum value of 22% moisture content in D2915–84 could imply that such an adjustment were possible. The moisture content adjustment procedures of D2915–84 are unchanged in the current version (D2915–98); the standard continues to suggest the limitation on a 5% maximum moisture content change. Table 7 compares adjustments from green to 15% and 12% average moisture content by current procedures given in D245 and D2915. These procedures could imply a significant difference in the change in predicted ultimate compressive stress parallel to grain.

ASTM D1990

As in the case of MOR, studies were conducted and models developed to predict changes in UCS parallel to grain associated with changes in moisture content (Barrett and Lau 1994). As with MOR, these models were judged too complex (Evans and others 1990), and the model chosen for ASTM D1990 was a simplified linear surface model of the following form (Fig. 6):

$$P_2 = P_1 \qquad \text{if UCS} \le 1{,}400 \text{ lb/in}^2$$

$$P_2 = P_1 + \left\{\frac{P_1 - 1{,}400}{34 - M_1}\right\}(M_2 - M_1) \qquad \text{if UCS} > 1{,}400 \text{ lb/in}^2 \tag{5}$$

where P_1 is property measured at moisture content M_1, P_2 is property predicted at moisture content M_2, and M_1 and M_2 are moisture contents (%).

As discussed for MOR, the lower limit of the model, below which UCS is assumed independent of moisture content, is 1,400 lb/in^2. The upper limit, above which the slope of the relationship between UCS and moisture content (UCS–MC)

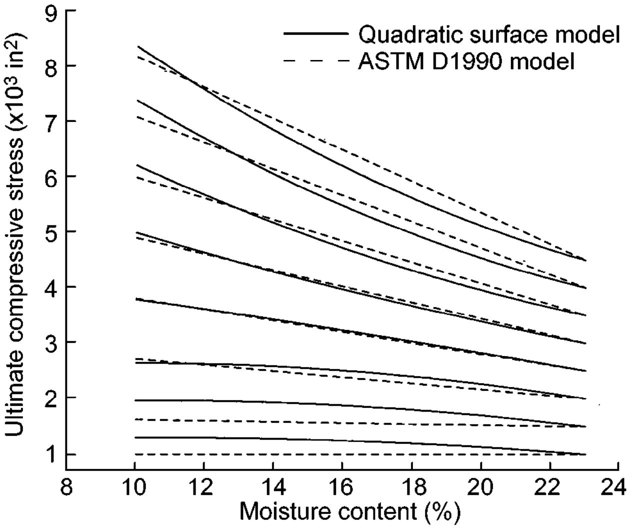

Figure 6—Effect of moisture content on compressive strength of lumber parallel to grain as predicted by quadratic surface model and ASTM D1990 model.

is held constant, is 4,400 lb/in^2 for green lumber. The “normalization” option discussed for MOR is also available for UCS (App. F). Equation (5) is assumed to be valid from 10% to 23% moisture content.

ASTM D1990 also contains “wet use” factors for adjusting allowable properties derived from the characteristic values at 15% moisture content using Equation (5) to green (Table 9). The allowable properties derived at 15% moisture content and the adjustment factors of Table 9 account for the normal shrinkage and swelling of lumber with changes in moisture content, as well as the changes in mechanical property values with change in moisture content. The basis of the adjustment factors (Table 9) is discussed in Appendix F.

Ultimate Tensile Stress Parallel to Grain

ASTM D245

Until the late 1950s, testing of full-size lumber specimens in ultimate tensile stress (UTS) parallel to grain was thought to be impossible because of the difficulty in gripping the specimen without causing premature failure near the grips. The ASTM D143 necked-down specimen for small clear members showed very high tensile strength for such specimens, but this was believed to be representative of the strength of large members. In fact, so little data were available that parallel-to-grain tensile strength of clear wood is not even discussed in the 1935 edition of the *Wood Handbook*. Given the familiar model of stresses in a bending specimen and the observation that in almost all bending tests of full-size lumber catastrophic failure occurred on the tensile side, it was assumed that MOR would be a reasonable measure of tensile strength. Thus, for the first half of the 20th century, no tests of lumber in tension were conducted. Researchers assumed that the allowable tensile stress equaled the allowable bending stress for all conditions of grade, moisture content, and other factors that affect strength.

ASTM D245–26T states that for “direct tension, the same values as for extreme fiber stress in bending may be used.” Nothing is specifically stated about moisture adjustments to tensile strength, but presumably these would be the same as those for bending. The same statement is made in D245–27. This statement would imply that the 25% rule applicable to bending members ≤4 in. thick would also be applicable to tensile strength. However, this assumption is not specifically stated in the first version of D245 (D245–26T) or later in Misc. Pub. 185, nor is the effect of moisture content on tensile strength discussed in the two supplements to Misc. Pub. 185. Moreover, moisture content adjustment to tensile strength is not stated in D245–49.

ASTM D245–57T specifically extends the use of the 25% rule to UTS. Although the technical justification for linking the moisture adjustments for tension with those for bending is not apparent, this change was consistent with the historic practice of deriving tensile strength from bending strength. Unpublished clear wood data available at the time (see 1974 and later editions of the *Wood Handbook*, which summarize clear wood tensile strength based on historical data) would have suggested an average increase of about 13% in the UTS of softwood species dried to 12% average (15% maximum) moisture content.

ASTM D245–69 continued the practice of assuming that bending strength is a conservative estimate of tensile strength and introduced the percentage increases currently (D245–99) allowed for lumber ≤4 in. thick manufactured and used at moisture content less than 15% or 19% (Table 6). Again, no test data appear to have been used to justify allowing the increases in MOR to be applied to UTS. Although ASTM D2555 does not contain dry-green ratios for tensile strength parallel to grain, UTS was assumed to be limited by the same percentage as was MOR.

ASTM D2915

ASTM D2915-70T was established to provide a method of assessing the appropriateness of assigned properties. As discussed in detail in the section on modulus of rupture, it was “suggested” in the standard that the moisture adjustment procedures reproduced in Equation (2) of this paper not be used for more than a 5% moisture content change. There was apparently no intent that this equation be used to adjust properties to (or from) green moisture content. However, the addition of a maximum value of 22% moisture content in D2915–84 could imply that such an adjustment were possible. The moisture content adjustment procedures of D2915–84 are unchanged in the current version (D2915–98); the standard continues to suggest the limitation on a 5% maximum moisture content change. Table 7 compares adjustments from green to 15% and 12% average moisture content by current procedures given in D245 and D2915. These procedures could imply an approximate 2% difference in the change in predicted UTS parallel to grain.

ASTM D1990

In support of the In-Grade program, a study was conducted on the effect of moisture content on the UTS of lumber parallel to grain of Douglas Fir dimension lumber (Green and others 1990). Green lumber in two commercial grades was obtained from one mill. Each grade of lumber was divided into four samples of about 120 specimens; three samples were equilibrated to 10%, 15%, and 20% moisture content and the fourth sample was tested green. As in the case of MOR, D1990 moisture content adjustments for UTS evolved from a quadratic surface model developed from the study used to adjust In-Grade data (Evans and others 1990). As with MOR, the concern was that the quadratic model predicted loss in strength with drying below approximately

13% to 15% moisture content and that the model was too complex for use in the standard.

The model chosen for ASTM D1990 was again a simplified linear surface model:

$$P_2 = P_1 \qquad \text{if UTS} \le 3{,}150 \text{ lb/in}^2$$

$$P_2 = P_1 + \left\{ \frac{P_1 - 3{,}150}{80 - M_1} \right\} \left(M_2 - M_1 \right) \qquad \text{if UTS} > 3{,}150 \text{ lb/in}^2 \tag{6}$$

where P_1 is property measured at moisture content M_1,
P_2 is property predicted at moisture content M_2, and
M_1 and M_2 are moisture contents (%).

The performance of this model, as compared with the more precise linear surface model, can be seen in Table 10 and is plotted in Figure 7. As with MOR, the model was limited to moisture contents above 10% because this was the lower limit of the data on which the model was based (Green and Evans 1989). As discussed for MOR, the lower limit of the model, below which UTS is assumed independent of moisture content, is 3,150 lb/in^2. The upper limit, above which the slope of the UTS–MC relationship is held constant, is 8,420 lb/in^2 for green lumber. As presented in the standard, Equation (6) is applicable to the lower tails of lumber strength distribution. As can be seen from Table 10, it may not be appropriate for adjusting UTS values at higher percentile levels. At the mean, the maximum absolute difference between the simplified model of Equation (6) and that of the more precise quadratic surface model is 128 lb/in^2 when adjusting from green to 12% moisture content; the quadratic surface model is more precise by about 36%. Thus, the ASTM model is appropriate only for adjusting lower tail properties of data from visual grades of lumber. The normalization option, as discussed for MOR, is also available for UTS (App. F).

ASTM D1990 also contains “wet use” factors for adjusting allowable properties derived from the characteristic values at 15% moisture content using Equation (6) to green (Table 9).

Table 10—Moisture content adjustment models for UTS at 15% moisture content[a] used to select adjustment models for ASTM D1991–91

	Average maximum absolute difference (lb/in^2)					
Model	Mean	5th	25th	50th	75th	95th
No adjustment	617	545	434	582	789	1,504
Quadratic surface	332	482	272	302	634	1,077
Linear surface, linear	460	553	385	452	633	1,172
Linear surface, cubic	460	519	349	461	641	1,155
Simplified model	460	541	402	450	626	1,172

[a]Based on data for Douglas Fir lumber.

The allowable properties derived at 15% moisture content and the adjustment factors of Table 9 account for the normal shrinkage and swelling of lumber with changes in moisture content, as well as the changes in mechanical property values with change in moisture content. The basis of the adjustment factors (Table 9) is discussed in Appendix F.

Compressive Strength Perpendicular to Grain

ASTM D245

As previously discussed for MOR, ASTM D245–27 provides working stresses at three moisture content levels: continuously dry, occasionally wet, and usually damp or wet. However, as previously discussed, these changes in properties were a response to decay hazard and not a change in compression perpendicular to grain strength values resulting from change in moisture content.

Also, as previously discussed in the section on MOR, ASTM D245–36T references Misc. Pub. 185 for a discussion of the development of working stresses. No specific changes related to moisture content effects on compression perpendicular to grain were made in the original publication or in the first supplement. However, the 1935 edition of the *Wood Handbook* does recommend a 30% reduction for members that will be continuously wet in service. Supplement 2 to Misc. Pub. 185 (FPL 1948) notes the following:

> The evaluation of fiber stress at proportional limit in compression perpendicular to grain is based largely on test specimens with the direction of growth rings, either parallel or perpendicular to the direction of applied force, while in

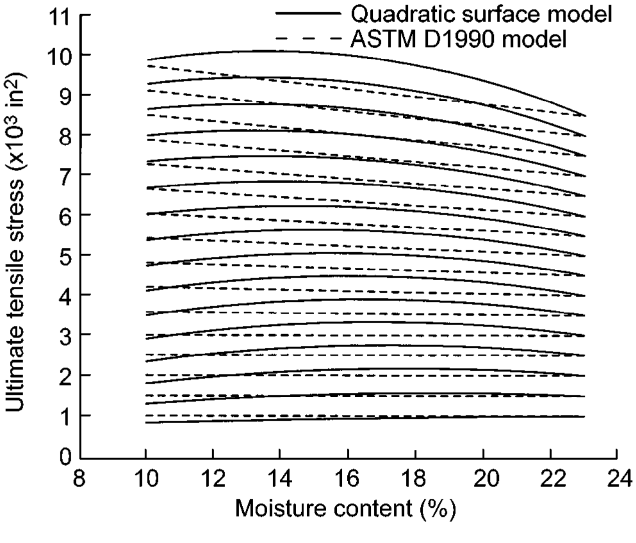

Figure 7—Effect of moisture content on tensile strength of lumber parallel to grain as predicted by quadratic surface model and ASTM D1990 model.

> the majority of structural timbers, the rings are at some intermediate angle. In view of the fact that bearing at an angle to the rings may be substantially less than those with rings parallel or perpendicular, the existing design values appear to be amply liberal, and no increase is recommended except for material which will be dry in service. (FPL 1948)

Supplement 2 also states "it is recommended that the basic stress values in compression perpendicular to grain…be increased 20% for seasoned material used under continuously dry conditions. Material surface dry when installed may be given stress values 10% higher…." Thus, a 20% increase was allowed if lumber was fully seasoned, but the increase was limited to 10% if only the surface of the lumber was dry.

Table X of D245–49T states that adjustments are to be made to perpendicular-to-grain compression for seasoning, but the standard includes no provisions for making these adjustments. Footnote c of table X states that "modifications of stresses in compression perpendicular to the grain for seasoning or moisture content are now under further study at the U.S. Forest Products Laboratory."

The next edition of ASTM D245 was D245–57T. Table IX of this version again states that seasoning adjustments are to be made and indicates that these increases apply to all sizes of lumber (that is, both dimension lumber and timbers). Paragraph 16f states that "working stresses in compression perpendicular to the grain may be increased by 50% above the value in table VIII (clear wood basic stresses) for lumber that will be continuously dry in use." This increase applied to lumber of all thicknesses. We have been unable to document the basis for this adjustment. Some information on research available on the effect of moisture content on strength in compression perpendicular to grain is given in Appendix G.

ASTM D245–69 does not provide an increase because of seasoning for compression perpendicular to grain of lumber 5 in. and more in thickness. The standard does provide a 50% increase in compression perpendicular to grain for lumber ≤4 in. thick regardless of the degree of seasoning. A footnote to table 8 of D245–69 states the following:

> 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. (ASTM D245)

The reasoning for the 50% increase was apparently that it was conservative relative to the dry-green ratio of small clear specimens (Robert Ethington, personal communication), which averages about 2.0 for softwoods and hardwoods (App. E). The moisture factors for compression perpendicular to grain of D245–69 (Table 6) still appear in the current version of the standard (D245–99).

ASTM D2915

ASTM D2915–
(Table 7). This has the effect of making the dry values equal to the green values, yet ASTM D245 allows a 50% increase regardless of the degree of drying. As discussed for MOR, this may be an example where the original intent of those that first established this standard was lost in revisions. If the original intent was simply to provide an equation for making changes in compression perpendicular to grain resulting from small changes in moisture content (later defined as ±5%), then assuming a factor of 1.0 made some sense (Robert Ethington, personal communication), especially if there were originally no intent to provide for adjusting values from dry to green (or vice versa). ASTM D245–70 assumed that a factor of 1.5 should be used to increase compression perpendicular to grain from green to dry, for all levels of dryness. Thus, the assumption that the factor was 1.0 between one dry level and another was consistent with D245. However, by 1984, when the equations were changed slightly to make a consistent assumption with regard to an assumed green moisture content, this original intent would seem to be forgotten. In the current form of the standard, users are not specifically prevented from making adjustments for moisture content changes greater than 5%. Thus, the apparent differences between the adjustments shown in D245 and D2915 can lead to confusion in the application of these standards.

ASTM D1990

Compressive strength perpendicular to grain is not determined in ASTM D1990. Rather, it is referenced to D245.

Shear Strength Parallel to Grain

ASTM D245

Prior to 1949, ASTM D245 included only one allowable shear strength for all moisture content levels, and no decrease was taken for decay hazard in the occasionally wet and usually wet service conditions. However, larger shake and checks were allowed for dry material than for green material in Circular 295 (Newlin and Johnson 1923) and in D245–26T. Thus, changes in performance because of seasoning were accounted for not by increasing the allowable shear strength but by changing the grade description for dry material, a practice to be followed for many years. The ratio of permitted shake for green and dry material is not a constant factor in the tables, and no further guidance is given in these two documents. The 1930 edition of D245 retains one shear value, but it adds the explicit statement that "shake in green material is assumed to reduce shearing stress in direct proportion to its extent. A greater amount of shake is permitted in seasoned material, made up for by the increased resistance of the remaining cross-section when seasoned."

As previously discussed in the section on MOR, ASTM D245–36T references Misc. Pub. 185 (Wilson 1934) for a discussion of the development of working stresses. This publication provides separate strength ratio tables for checks, shake, and splits for both green and dry lumber. The strength ratio tables for dry lumber are approximately 9/8 those for green lumber. Forest Products Laboratory report GTR–23 (Ethington and others 1979) identifies Misc. Pub. 185 (Wilson 1934) as the first to recommend an increase in working stresses in shear for dry material. As previously discussed, this is not strictly true, but Misc. Pub. 185 was the first to suggest a specific relationship between green and dry shear values. We did not find an explicit statement of a 9/8 factor in Misc. Pub. 185. Rather, the factor was deduced by comparison of the formula for deriving the permissible size of shake given in footnotes (a) and (b) to table 5 of Misc. Pub. 185:

$$\begin{aligned} S_{\text{green}} &= (100 - R_{\text{green}})/100 \\ S_{\text{dry}} &= (900 - 8R_{\text{dry}})/900 \end{aligned} \qquad (7)$$

where S is permissible size of shake as a fraction of nominal width and R is strength ratio (%).

Equating the two values for S in Equation (7) yields

$$R_{\text{dry}} = (9/8)\, R_{\text{green}}$$

Misc. Pub. 185 does not explain the data, or logic, behind the 9/8 increase. A factor of 9/8 (or 1.125) is considerably less than the average value of the dry-green ratio obtained from block shear tests on small clear specimens. It seems likely that the 9/8 factor was based on differences between dry and green shear strength of beam specimens that failed in shear (App. H).

ASTM D245–49T was the first revision of the standard since 1936. It included the dry and green strength ratio tables of Misc. Pub. 185 and thus the 9/8 factor for all thickness of dry lumber. Footnote b of table X in D245–49 noted that “modifications for seasoning (for joist and plank) in current commercial practice is accomplished by liberalizing defects in grade rather than increasing working stresses.”

In ASTM D245–57T, the 1/8 increase in the strength ratios for shake in dry lumber of all sizes was retained, but the footnote (now to table IX of the standard) was replaced by “modifications for seasoning in joist and plank may be accomplished either by liberalizing grade limitations or by increasing working stresses.” Separately, D245–57T also stated the following:

> Working stresses for all grades of 1- or 2-in. (nominal) lumber that is dressed at 15% or lower moisture content and is fabricated and used under conditions where that moisture content is not exceeded, may be increased…by one-eighth in horizontal shear…. (ASTM D245)

ASTM D245–64T retained the provisions of D245–57T and added an 8% increase in horizontal shear with 1- or 2-in.-thick lumber if the maximum moisture content were 19% and the lumber were used under continuously dry conditions.

In D245–69, the footnote to the table (now table 7) vanished, as did the strength ratio table for shake or splits in dry lumber. A new table showed allowable increases in allowable stress for seasoning for lumber ≤4 in. thick (Table 6). The 1/8 increase for lumber with maximum moisture content of 15% was rounded to 13%, and the 8% increase for lumber with maximum moisture content of 19% was maintained. The restriction that “the increase for 15% maximum moisture content shall not exceed the ratio of dry to green clear wood strength shown in…D2555” was added to the standard. Furthermore, the standard states that “where ratios in D2555 are less than above, proportionate reductions shall be made in lumber at 19% maximum moisture content.” No factors for seasoning are given for lumber 5 in. or more in thickness. These adjustments are retained in the current version of the standard (D245–99).

ASTM D2915

As with other properties, adjustments to increase shear properties of dimension lumber consistent with those of ASTM D245 were provided in D2915–70T (Eq. (2), Table 7). In 1984, modification of D2915 to assume lumber moisture content was no higher than 22% for all properties resulted in a higher increase for shear than was provided by D245 (Table 7). The ASTM committee apparently decided that these differences were justified. However, as discussed for MOR and compression perpendicular to grain, this may have also been an instance where the original intent of the 1970 version of the standard was lost to future generations of ASTM members.

ASTM D1990

Shear strength parallel to grain is determined by reference to ASTM D245.

Summary of Changes to Standards

The chronology of changes to ASTM standards presented in this report particularly focuses on ASTM D245 because it is the oldest standard for adjusting the allowable properties of lumber for changes in moisture content. ASTM D245 bases allowable properties on tests of small clear specimens, but procedures for adjusting lumber properties for change in moisture content are not always based on clear wood data. Table 11 summarizes changes to moisture content adjustment procedures in D245. This table enables the reader to follow potential logical changes over the years and to see

Table 11—Summary of changes in adjustment procedures to allowable properties in ASTM D245 as a result of moisture content changes[a]

		Nominal thickness of lumber[b]		
Property	Edition of standard	>4 in.	2 to 4 in.	1 to 2 in.
MOR	1926T	None	25% rule	—
	1957T	None	25% rule	or 25% if ≤15% MC
	1964T	None	25% rule	or 15% if ≤19% MC
				or 25% if ≤15% MC
	1969	None	35% if ≤15% MC	same as for 2 to 4 in.
			25% if ≤19% MC	same as for 2 to 4 in.
MOE	1926T	None	None	—
	1957T	10%	10%	or 10% if ≤15% MC
	1964T	10%	10%	or 14% if ≤19% MC
				or 20% if ≤15% MC
	1969	2%	14% if ≤19% MC	same as for 2 to 4 in.
			20% if ≤15% MC	same as for 2 to 4 in.
UCS	1926T	None	None	—
	1936T	None	25% rule	—
	1957T	10%	25% rule + 10%	or 37.5% if ≤15% MC
	1964T	10%	25% rule + 10%	or 37.5% if ≤15% MC
				or 22% if ≤19% MC
	1969	10%	75% if ≤15% MC	same as for 2 to 4 in.
			50% if ≤19% MC	same as for 2 to 4 in.
UTS	1926T	None	25% rule[c]	—
	1957T	None	25% rule	or 25% if ≤15% MC
	1964T	None	25% rule	or 15% if ≤19% MC
				or 25% if ≤15% MC
	1969	None	35% if ≤15% MC	same as for 2 to 4 in.
			25% if ≤19% MC	same as for 2 to 4 in.
C–perp[d]	1926T	None	None	—
	1937[e]	20% if thoroughly dry	20% if thoroughly dry	—
		10% surface dry	10% surface dry	—
	1949T	NR	NR	NR
	1957T	50%	50%	same as for 2 to 4 in.
	1969	None	50%	same as for 2 to 4 in.
Shear	1926T	(f)	(f)	—
	1957T	(f)	or 12.5%[f]	or 12.5% if ≤15% MC
	1964T	(f)	or 12.5%[f]	or 12.5% if ≤15% MC
				or 8% if ≤19% MC
	1969	None	13% if ≤15% MC	same as for 2 to 4 in.
			8% if ≤19% MC	same as for 2 to 4 in.

[a] In some periods, it was possible to liberalize the grade description for dry lumber rather than increase the allowable property. Beginning in 1969, adjustments could not be greater than the dry/green ratio for the species as given in ASTM D2555.

[b] NR designates no recommendations provided.

[c] Beginning with D245–26T, it was assumed that UTS was equal to MOR. It is assumed that the 25% rule applied to UTS, but this was not stated.

[d] Compression perpendicular to grain.

[e] ASTMD245–37 changed automatically with modifications to Misc. Pub. 185. Such a change occurred with Supplement 2 (FPL 1948) (see text).

[f] From 1926 through 1933, the increase in strength ratio for shake in dry lumber varied somewhat with width. Beginning with 1936T, the increase in strength ratio for dry lumber was 9/8 (a 1/8 or 12.5% increase).

how these changes were made for each of the six properties currently used in design specifications. The alternative of liberalizing the grade description instead of increasing a specific allowable property is included in Table 11 only as a footnote. As discussed in the text, this option was historically taken by grading agencies, especially with respect to shear strength. Also note that D245 is the only ASTM standard that contains provisions for adjusting the properties of ≥4-in.-thick lumber for changes in moisture content. For timbers, these provisions have remained unchanged for at least 30 years.

This report also includes discussion of the development of two relatively new standards for deriving allowable lumber properties based on tests of lumber containing defects and naturally occurring growth characteristics. These standards are D2915 (first adopted in 1970) and D1990 (first adopted in 1991). Table 12 presents a simplified summary of how the current versions of these standards handle moisture adjustment procedures for ≤4-in.-thick lumber. Because the D2555 dry-green ratios were adopted as an “override” in D245 in 1969, Table 12 also includes average values from these results for softwood species as points of comparison. In D1990–97, the adjustments for MOR, UTS, and UCS depend upon the initial green strength of the lumber. Thus, for green lumber with MOR of 6,000 lb/in^2, the property would be increased 39% when the value was adjusted to an average moisture content of 12%, while a lower quality piece with MOR of 2,000 lb/in^2 would get no adjustment.

Recommendations

As the text indicates, the procedures in D245, D2915, and D1990 show some very significant differences. As D2915 and D245 evolved, some of their apparent differences may have resulted from ASTM task group members reading inferences into D2915 formulas in a manner not intended by the original framers of this standard. Some differences between D1990 and D245 are the result of failure to update D245 in light of more recent information on the effect of moisture content on the properties of 2- to 4-in.-thick dimension lumber. Note that differences also exist between the standards in how other adjustment procedures are handled.

The challenge is not to simply use the same adjustment procedures in all three standards, but rather to have each standard produce equivalent allowable properties for the same material. Although they have different objectives, both D2915 and D1990 start with test data generated from tests of full-size structural lumber. Thus, adjustment procedures in these two standards would seemingly be the easiest to reconcile, and perhaps this is where the first attempts should be made. Once consensus is reached on adjustment procedures in D2915 and D1990, the greater challenge of modifying D245 might be somewhat easier. D245 presents a greater challenge because it starts with test data from small clear specimens. There are many alternatives to modifying this standard so that it produces results consistent with the other two standards. Which approach is the best from a technical perspective or which would be the easiest for reaching a consensus opinion is not clear.

Table 12—Ratio of property at 12% moisture content to that of green dimension lumber by various ASTM standards[a]

Standard	MOR	UTS	MOE	UCS	Shear	C–perp
D245–99	1.35	1.35	1.20	1.75	1.13	1.50
D2915–98[b]	1.33	1.33	1.20	1.91	1.17	1.00
D2555–98[c]	1.69	—	1.25	1.99	1.47	2.03
D1990–97			1.18		—	—
6,000 lb/in^2	1.39	1.09	1.18	NA	—	—
5,000 lb/in^2	1.33	1.07	1.18	NA	—	—
4,000 lb/in^2	1.26	1.04	1.18	1.65	—	—
3,000 lb/in^2	1.13	1.00[d]	1.18	1.53	—	—
2,000 lb/in^2	1.00[d]	1.00[d]	1.18	1.30	—	—
1,000 lb/in^2	1.00[d]	1.00[d]	1.18	1.00[d]	—	—

[a] NA indicates that the green value is higher than the applicable range of adjustment (9,600 lb/in^2 for MOR, 8,400 lb/in^2 for UTS, and 4,400 lb/in^2 for UCS); significant error may occur. Arrow (
property under D1990–97 may vary with initial green strength. Refer to strength values listed in the table.

[b] Adjusting over this moisture content range may not be within the intent of the standard (see text).

[c] D2555 values are the average for all softwood species, for small clear specimens (App. E).

[d] Adjustment is 1.0 below 2,400 lb/in^2 for MOR, 3,150 lb/in^2 for UTS, and 1,400 lb/in^2 for UCS.

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Appendix A—First Consensus Recommendations for Strength of Bridge and Trestle Timbers

Recommendations for timber strength were presented in 1895 by a committee of the American International Association of Railway Superintendents of Bridges and Buildings (Berg and others 1907). The committee's report, reproduced in part here, included a summary of all available property data collected from many sources from about 1870 to 1895 as well as design equations.

Report of Committee on "Strength of Bridge and Trestle Timbers"

Your committee appointed to report on "Strength of Bridge and Trestle Timbers, with special reference to Southern Yellow Pine, White Pine, Fir, and Oak," desire to present herewith, as part of their report, the very valuable data compiled by the chairman of the committee, relative to tests of the principal American bridge and trestle timbers and the recommendations of the leading authorities on the subject of strength of timber during the last twenty-five years, embodied in the appendix to this report and tabulated for easy reference in the accompanying tables I to IV.

The uncertainty of our knowledge relative to the strength of timber is clearly demonstrated after a perusal of this information, and emphasizes, better than long dissertations on the subject, the necessity for more extensive, thorough, and reliable series of tests, conducted on a truly scientific basis, approximating, as nearly as possible, actual conditions encountered in practice.

The wide range of values recommended by the various recognized authorities is to be regretted, especially so when undue influence has been attributed by them in their deductions to isolated tests of small size specimens, not only limited in number, but especially defective in not having noted and recorded properly the exact species of each specimen tested, its origin, condition, quality, degree of seasoning, method of testing, etc.

Great credit is due to such investigators and experimenters as Professors G. Lanza, J.B. Johnson, H.T. Bovey, C.B. Wing, and Messrs. Onward Bates, W.H. Finley, C.B. Talbot, and others, for their experimental work and agitation in favor of full size tests. Professors G. Lanza, R.H. Thurston, and William H. Burr have contributed valuable treatises on the subject of strength of timber. The extensive series of small and full size United States government tests, conducted in 1880 to 1882, at the Watertown arsenal, under Col. T.T.S. Laidley, and more recently the very elaborate and thorough timber tests being conducted by the United States Forestry Division under Dr. B.E. Fernow, chief, and Professor J.B. Johnson of Washington University, St. Louis, afford us to-day, in connection with the work of the above-mentioned experimenters, our most reliable data from a practical standpoint.

The test data at hand and the summary criticisms of leading authorities seem to indicate the general correctness of the following conclusions.

1. Of all structural materials used for bridges and trestles timber is the most variable as to the properties and strength of different pieces classed as belonging to the same species, hence impossible to establish close and reliable limits of strength for each species.

2. The various names applied to one and the same species in different parts of the country lead to great confusion in classifying or applying results of tests.

3. Variations in strength are generally directly proportional to the density or weight of timber.

4. As a rule, a reduction of moisture is accompanied by an increase in strength; in other words, seasoned lumber is stronger than green lumber.

5. Structures should be in general designed for the strength of green or moderately seasoned lumber of average equality and not for a high grade of well-seasoned material.

6. Age or use do not destroy the strength of timber, unless decay or season-checking takes place.

7. Timber, unlike materials of a more homogeneous nature, as iron and steel, has no well defined limit of elasticity As a rule, it can be stained very near to the breaking point without serious injury, which accounts for the continuous use of many timber structures with the material strained far beyond the usually accepted safe limits. On the other hand, sudden and frequently inexplicable failures of individual sticks at very low limits are liable to occur.

8. Knots, even when sound and tight, are one of the most objectionable features of timber, both for beams and struts. The full size tests of every experimenter have demonstrated, not only that beams break at knots, but that invariably timber struts will fail at a knot or owing to the proximity of a knot, by reducing the effective area of the stick and causing curly and cross-grained fibers, thus exploding the old practical view that sound and tight knots are not detrimental to timber in compression.

9. Excepting in top logs of a tree or very small and young timber, the heart-wood is, as a rule, not as strong as the material farther away form the heart. This becomes more generally apparent, in practice, in large sticks with considerable heart-wood cut from old trees in which the heart has begun to decay or been wind-shaken. Beams cut from such material frequently season-check along middle of beam and fail by longitudinal shearing.

10. Top logs are not as strong as butt logs, provided the latter have sound timber.

11. The results of compression tests are more uniform and vary less for one species of timber than any other kind of test; hence, if only one kind of test can be made, it would seem that a compressive test will furnish the most reliable comparative results.

12. Long, timber columns generally fail by lateral deflection or "buckling" when the length exceeds the least cross-sectional dimension of the stick by twenty, in other words, the column is longer than twenty diameters. In practice the unit stress for all columns over fifteen diameters should be reduced in accordance with the various rules and formulae established for long columns.

13. Uneven end-bearing and eccentric loading of columns produce more serious disturbances than usually assumed.

14. The tests of full-size, long, compound columns, composed of several sticks bolted and fastened together at intervals, show essentially the same ultimate unit resistance for the compound column as each component stick would have if considered as a column by itself.

15. More attention should be given in practice to the proper proportioning of bearing area; in other words, the compressive bearing resistance of timber with and across grain, especially the latter, owing to the tendency of an excessive crushing stress across grain to indent the timber, thereby destroying the fiber and increasing the liability to speedy decay, especially when exposed to the weather and the continual working produced by moving loads.

The aim of your committee has been to examine the conflicting test data at hand, attributing the proper degree of importance to the various results and recommendations, and then to establish a set of units that can by accepted as fair average values, as far as known to-day, for the ordinary quality of each species of timber and corresponding to the usual conditions and sizes of timber encountered in practice. The difficulties of executing such a task successfully cannot be overrated, owing to the meagerness and frequently the indefiniteness of the available test data, and especially the great range of physical properties in different sticks of the same general species, not only due to the locality where it is grown, but also to the condition of the timber as regards the percentage of moisture, degree of seasoning, physical characteristics, grain, texture, proportion of hard and soft fibers, presence of knots, etc., all of which affect the question of strength.

Your committee recommends, upon the basis of the test data at hand at the present time, the average units for the ultimate breaking stresses of the principal timbers used in bridge and trestle constructions shown in the accompanying table.

In addition to the units given in the table, attention should be called to the latest formulae for long timber columns, mentioned more particularly in the Appendix to this report, which formulae are based upon the results of the more recent full-size timber column tests, and hence should be considered more valuable than the older formulae derived from a limited number of small-size tests. These new formulae are Professor Burr’s, App. I.; Professor Ely’s, App. J.; Professor Stanwood’s, App. K., and A.L. Johnson’s App. V.; while C. Shaler Smith’s formulae will be better understood after examining the explanatory notes contained in App. L.

Attention should also be called to the necessity of examining the resistance of a beam to longitudinal shearing along the neutral axis, as beams under transverse loading frequently fail by longitudinal shearing in place of transverse rupture.

In addition to the ultimate breaking unit stress the designer of a timber structure has to establish the safe allowable unit stress for the species of timber to be used. This will vary for each particular class of structures and individual conditions. The selection of the proper “factor of safety” is largely a question of personal judgment and experience, and offers the best opportunity for the display of analytical and practical ability on the part of the designer. It is difficult to give specific rules. The following are some of the controlling questions to be considered.

The class of structure, whether temporary or permanent, and the nature of the loading, whether dead or live. If live, then whether the application of the load is accompanied by severe dynamic shocks and pounding of the structure. Whether the assumed loading for calculations is the absolute maximum rarely to be applied in practice, or a possibility that may frequently take place. Prolonged heavy, steady loading, and also alternate tensile and compressive stresses in the same place, will call for lower averages. Information as to whether the assumed breaking stresses are based on full-size or small-size tests, or only on interpolated values averaged from tests of similar species of timber, is valuable, in order to attribute the proper degree of importance to recommended average values. The class of timber to be used, and its condition and quality. Finally, the particular kind of strain the stick is to be subjected to, and its position in the structure with regard to its importance and the possible damage that might be caused by its failure.

In order to present something definite on this subject, your committee presents the accompanying table showing the average safe allowable working unit stresses or the principal bridge and trestle timbers, prepared to meet the average conditions existing in railroad timber structure, the units being based upon the ultimate breaking unit stresses recommended by your committee and the following factors of safety, viz.:

Tension, with and across grain	10
Compression, with rain	5
Compression, across grain	4
Transverse, extreme fiber stress	6
Transverse, modulus of elasticity	2
Shearing, with and across grain	4

In conclusion, your committee desires to emphasize the importance and great value to the railroad companies of the country of the experimental work on the strength of American timbers being conducted by the Forestry Division of the United States Department of Agriculture, and to suggest that the American Association of Railway Superintendents of Bridges and Buildings endorse this view by official action, and lend its aid in every way possible to encourage the vigorous continuance of this series of government tests, which bids fair to become the most reliable and useful work on the subject of strength of American timbers ever undertaken. With additional and reliable information on this subject, far-reaching economies in the designing of timber structures can be introduced, resulting not only in a great pecuniary saving to the railroad companies, but also offering a partial check to the enormous consumption of timber and the gradual diminution of our structural timber supply.

WALTER, G. BERG, *Chairman*,
J. H. CUMMIN,
JOHN FOREMAN,
H.L.FRY,

Committee.

Appendix B—Moisture Content Effects on Flexural Properties of ≥5-in.-Thick Timbers

As discussed in the text, analysis of data from Bulletin 108 (Cline and Heim 1912), as well as engineering judgment, led to the conclusion that although the strength of timbers increases with seasoning, this increase may be offset by weakening of the timber as a result of the formation of splits. Later versions of ASTM D245 maintained this philosophy for modulus of rupture (MOR), but they allowed a 2% increase in modulus of elasticity (MOE) for lumber dried to a maximum moisture content of 15% (average 12%). However, the data in Bulletin 108 (summarized in Table 1 in the text) is not the best place to determine the possible magnitude of property increases for timbers. This is because the green and dry pieces in the data sets for any given species are not necessarily of equal quality, and the green and dry data sets may have much different sample sizes. Other historical data are available that are better suited to making judgments about the effect of seasoning on changes in properties. Such information may be useful to those making decisions on the degree of conservatism incorporated into ASTM standards and to those conducting research on the properties of timbers.

Data on approximately 50 green and dry Sitka spruce and western hemlock 8- by 12-in. timbers cut in Alaska were reported in USDA Technical Bulletin 226 (Markwardt 1931). Each of the selected logs was 32 ft long. Half of each log was used to obtain a dry timber and the other half to obtain a green timber. The dry timber was obtained from the butt log of half the trees (25 trees) and from the top log of the other half. By current standards, the timbers were generally of high quality. Approximately 86% of western hemlock timbers and 95% of Sitka spruce timbers were graded as S2, later called Select, by the rules of USDA Circular 295 (Newlin and Johnson 1923).[4] Thus, most of these timbers would have been graded as Select Structural by current grading rules.

The timbers were shipped to the Forest Products Laboratory, cut in half, and the green beams immediately tested. The remaining members were then air dried for several years prior to testing. All timbers were tested as simply supported beams, on edge in one-third point bending, using a span-to-depth ratio of approximately 11:1. The MOE of both species increased approximately 12% in drying to about 17% moisture content. Mean MOR increased about 20% and 5th percentile MOR by about 9% (Table B1).

An earlier study (Cline and Knapp 1911) on ten 32-ft-long Douglas-fir 8- by 16-in. timbers had been conducted in a manner similar to that described in Bulletin 226, except that dry specimens were not taken alternately from butt and top logs (Table B1). In this study, MOE increased about 13% in drying the lumber to about 16% moisture content and mean MOR increased about 24%.

Betts (1909) presented data on loblolly pine timbers seasoned slowly under cover for 21 months. Mean MOE of these pieces increased 16% in drying to 18% moisture content and mean MOR about 20% (Table B1).

Littleford (1967) presented the results of tests conducted in Canada many years earlier on Douglas-fir nominal 6- by 12-in. lumber. These beams were tested on edge in one-third-point bending with a span-to-depth ratio of approximately 15:1. Mean MOE of these timbers increased about 9% in drying to a moisture content of about 17% (Table B1). Mean MOR increased about 23% in drying and the 5th percentile MOR about 17%.

These data demonstrate the increases in properties that might occur when timbers are dried slowly to a moisture content of about 17%, as, for example, might occur with timbers that were installed green in a building and then dried in place. The data also show the degree of the conservative assumptions of D245. As with dimension lumber, the increase in 5th percentile MOR with drying is less than that of the mean value.

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[4] The minimum estimated strength ratio for this historical grade was 75%.

Table B1—Historical data on the effect of moisture content on flexural properties of slowly dried timbers

Species, timber size, and reference[a]	Condition	Sample size	Moisture content (%)			Mean MOE		MOR			
								Mean		5th percentile	
			Mean	Low	High	GPa	$\times 10^6$ lb/in^2	MPa	$\times 10^3$ lb/in^2	MPa	$\times 10^3$ lb/in^2
Sitka spruce	Green	20	34.4	29	53	8.569	1.243	29.823	4.326	23.00	3.48
8 by 16 (1)	Dry	20	17.3	14	23	9.660	1.401	36.614	5.311	25.00	3.77
	Dry/green	—	—	—	—	1.127	1.127	1.228	1.228	1.08	1.08
Western hemlock	Green	28	41.6	31	59	9.362	1.358	33.636	4.879	25.78	3.74
8 by 16 (1)	Dry	29	17.5	16	19	10.486	1.521	39.620	5.747	28.47	4.13
	Dry/green	—	—	—	—	1.120	1.120	1.178	1.178	1.10	1.10
Douglas-fir	Green	10	31.0	26	36	9.907	1.437	37.503	5.440	—	—
8 by 16 (2)	Dry	10	16.4	15	17	11.175	1.621	46.466	6.740	—	—
	Dry/green	—	—	—	—	1.128	1.128	1.239	1.239	—	—
Douglas-fir	Green	26	35.1	—	—	11.203	1.625	42.240	6.127	33.73[b]	4.89
6 by 12 (3)	Dry	28	17.4	—	—	12.182	1.767	51.996	7.542	39.61[b]	5.75
	Dry/green	—	—	—	—	1.087	1.087	1.231	1.231	1.17	1.17
Southern Pine	Green	12	50.9	36	79	10.000	1.450	38.744	5.620	—	—
8 by 16 (4)	Dry	12	19.7	22	18	11.637	1.688	46.335	6.721	—	—
	Dry/green	—	—	—	—	1.164	1.164	1.196	1.196	—	—

[a] References: (1) Markwardt 1931, (2) Cline and Knapp 1911, (3) Littleford 1967, (4) Betts 1909.

[b] Calculated using an assumed normal distribution.

Appendix C—Chronology of ASTM D245

Date	Title of standard
1926T	Tentative specifications for structural wood joist and planks, beams and stringers, and posts and timbers
1927	Standard specifications for structural wood joist and planks, beams and stringers, and posts and timbers
1930	Standard specifications for structural wood joist and planks, beams and stringers, and posts and timbers
1933	Standard specifications for structural wood joist and planks, beams and stringers, and posts and timbers
1936T	Tentative specifications for structural wood joist and plank, beams and stringers, and posts and timbers
1937	Standard specifications for structural wood joist and planks, beams and stringers, and posts and timbers
1949T	Tentative methods for establishing structural grades of lumber
1957T	Tentative methods for establishing structural grades of lumber
1962T	Tentative methods for establishing structural grades of lumber
1964T	Tentative methods for establishing structural grades of lumber
1968T	Tentative standard methods for establishing structural grades and related allowable properties for visually graded lumber. This standard does not appear in either the 1968 or 1969 Annual Book of Standards.
1969	Standard methods for establishing structural grades and related allowable properties for visually graded lumber
1970	Standard methods for establishing structural grades and related allowable properties for visually graded lumber
1974	Standard methods for establishing structural grades and related allowable properties for visually graded lumber
1981	Standard methods for establishing structural grades and related allowable properties for visually graded lumber
1988	Standard practice for establishing structural grades and related allowable properties for visually graded lumber
1992	Standard practice for establishing structural grades and related allowable properties for visually graded lumber
1993	Standard practice for establishing structural grades and related allowable properties for visually graded lumber
1998	Standard practice for establishing structural grades and related allowable properties for visually graded lumber
1999	Standard practice for establishing structural grades and related allowable properties for visually graded lumber

Appendix D—Allowable Properties in Bending of Select (S2) Grade in Early Documents

Appendix D includes data from two seminal documents by Newlin and Johnson for establishing working stresses and grading rules: Circular 295, published in 1923, and an unpublished memorandum of 1924. Circular 295 provides grade descriptions for the four grades (S1, S2, S3, and S4) later associated with Extra Select, Select Structural, Standard, and Common grades. In the unpublished memorandum, Newlin and Johnson discuss the factors involved in determining the working stresses provided in Circular 295.

This appendix also includes data from ASTM D245–27, the first standard specifications for structural wood joists and planks, beams and stringers, and posts and timbers.

Circular 295 (Newlin and Johnson 1923)

Table 1—Working stresses permissible for structural timber of Select (S2) grade[a] (pounds per square inch)

	Bending					Compression					
	Allowable stress in extreme fiber for Select (S2) grade					Allowable stress parallel to grain "Short Columns"[c] for Select (S2) grade			Allowable stress perpendicular to grain for all grades		
Species	Damp or wet location (docks, piling, and sills)	Outside, not in contact with soil (bridges and open sheds)	Under shelter in dry location (factories and warehouses)	Allowable horizontal shear stress Select (S2) grade—all locations	Allowable modulus of elasticity for all grades—all locations	Wet location	Dry outside location	Dry inside location	Wet location	Dry outside location	Dry inside location
Ash, black	800	900	1,000	90	1,100,000	500	550	650	150	200	300
Ash, commercial white (green, Biltmore, white)	1,000	1,200	1,400	125	1,500,000	900	1,000	1,100	300	375	500
Aspen and large-tooth aspen	500	650	800	80	900,000	450	550	700	100	125	150
Basswood	500	650	800	80	900,000	450	550	700	100	125	150
Beech	1,000	1,300	1,500	125	1,600,000	900	1,100	1,200	300	375	500
Birch, paper	600	750	900	80	1,000,000	450	550	650	100	150	200
Birch, yellow and sweet	1,000	1,300	1,500	120	1,000,000	900	1,100	1,200	300	375	500
Cedar, Alaska	800	900	1,000	90	1,100,000	650	750	800	150	200	250
Cedar, western red	750	800	900	80	1,000,000	650	700	700	125	150	200
Cedar, northern and southern white	600	650	750	70	800,000	450	500	550	100	140	175
Cedar, Port Orford	900	1,000	1,100	100	1,200,000	750	825	900	150	200	250
Chestnut	700	850	950	90	1,000,000	600	700	800	150	200	300
Cottonwood, common and black	500	650	800	80	900,000	450	550	700	100	125	150
Cypress, bald	900	1,100	1,300	100	1,400,000	800	1,000	1,100	225	250	350
Douglas fir (western Washington and Oregon)[b]	1,000	1,300	1,500	90	1,600,000	850	1,000	1,100	200	225	325
Douglas fir (Rocky Mountain type)	700	900	1,100	85	1,200,000	700	800	800	200	225	275
Elm, cork	1,000	1,300	1,500	125	1,300,000	900	1,100	1,200	300	375	500
Elm, slippery and white	800	900	1,100	100	1,200,000	650	750	800	125	175	250
Fir, balsam	600	750	900	70	1,000,000	500	600	700	100	125	150
Fir, commercial white (white, noble, grand)	800	900	1,100	70	1,200,000	650	750	800	150	200	300
Gum, black and cotton	800	900	1,100	100	1,200,000	650	750	800	150	200	300
Gum, red	800	900	1,100	100	1,200,000	650	750	800	150	200	300
Hemlock, western	900	1,100	1,300	75	1,400,000	800	900	900	200	225	300
Hemlock, eastern	800	900	1,000	70	1,100,000	600	700	700	200	225	300
Hickory, true and pecan	1,200	1,500	1,900	140	1,800,000	1,000	1,200	1,500	350	400	600
Larch, western	900	1,100	1,200	100	1,300,000	800	1,000	1,100	200	275	325
Maple, sugar and black	1,000	1,300	1,500	150	1,600,000	900	1,100	1,200	300	375	500
Maple, red and silver	700	900	1,000	100	1,100,000	600	700	800	200	250	350
Oak, commercial red and white	1,000	1,200	1,400	125	1,500,000	800	900	1,000	300	375	500
Pine, southern yellow[b]	1,000	1,300	1,500	110	1,600,000	850	1,000	1,100	200	225	325
Pine, white, sugar, western white, western yellow	750	800	900	85	1,000,000	650	750	750	125	150	250
Pine, Norway	800	1,000	1,100	85	1,200,000	700	800	800	150	175	300
Poplar, yellow	800	900	1,000	80	1,100,000	600	700	800	125	150	250
Redwood	800	1,000	1,200	70	1,200,000	750	900	1,000	125	150	250
Spruce, red white, Sitka	800	900	1,100	85	1,200,000	650	750	800	125	150	250
Spruce, Engelmann	500	650	750	70	800,000	450	550	600	100	140	175
Sycamore	800	900	1,100	80	1,200,000	650	750	800	150	200	300
Tamarack, eastern	900	1,100	1,200	95	1,300,000	800	900	1,000	200	225	300

[a] Working stresses for Extra Select (S1), Extra Select (S1) Dense, Standard (S3), and Common (S4) grades are obtained by multiplying the basic stress by 7/6, 8/6, 5/6, and 4/6, respectively.

[b] The working stresses of any grade of timbers of Douglas fir and southern yellow pine, which meet the density requirements of the American Society of Testing Materials shall be increased one-sixth the allowable stress given in the table for the basic or Select (S2) grade.

[c] The influence of knots on compressive strength of columns of constant cross section decreases as the length increases. When the length reaches 30 times the least dimension, knots such as are allowable in Select (S2) timbers have no appreciable effect on the strength as a column.

Newlin and Johnson 1924, unpublished memo

Working stresses permissible for structural timbers of Select (S2) grade[a] (pounds per square inch)

	Bending									Compression					
	Stress in extreme fiber									Stress parallel to grain, short columns,[c] all sizes (location)			Stress perpendicular to grain, all sizes (location)		
	Damp or wet locations (docks, caps, and sills) all sizes	Outside locations (bridges and open sheds) all sizes	Under shelter in dry locations					Allowable horizontal shear stress, all locations, all sizes	Average modulus of elasticity for all locations and sizes[b]	Wet	Dry outside	Dry inside	Wet	Dry outside	Dry inside
			Beams (factory and warehouse) 6 in. thick and over	Joists (houses, stores, and light warehouses) 4 in. thick and under											
Species		Select (S2)[b]		S1	S2	S3	S4	Select (S2)	All grades		Select (S2) grade			All grades	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
Ash, black	800	900	1,000	1,420	1,170	920	670	90	1,100,000	500	550	650	150	200	300
Ash, commercial white (green, Biltmore, white	1,000	1,200	1,400	1,980	1,630	1,280	930	125	1,500,000	900	1,000	1,100	300	375	500
Aspen and largetooth aspen	500	650	800	1,130	930	730	530	80	900,000	450	550	700	100	125	150
Basswood	500	650	800	1,130	930	730	530	80	900,000	450	550	700	100	125	150
Beech	1,000	1,300	1,500	2,120	1,750	1,370	1,000	125	1,600,000	900	1,100	1,200	300	375	500
Birch, paper	600	750	900	1,270	1,050	820	600	80	1,000,000	450	550	650	100	150	200
Birch, yellow and sweet	1,000	1,300	1,500	2,120	1,750	1,370	1,000	120	1,600,000	900	1,100	1,200	300	375	500
Cedar, Alaska	800	900	1,000	1,420	1,170	920	670	90	1,100,000	650	750	800	150	200	250
Cedar, western red	750	800	900	1,270	1,050	820	600	80	1,000,000	650	700	700	125	150	200
Cedar, northern and southern white	600	650	750	1,060	880	690	500	70	800,000	450	500	550	100	140	175
Cedar, Port Orford	900	1,000	1,100	1,560	1,280	1,010	730	100	1,200,000	750	825	900	150	200	250
Chestnut	700	850	950	1,350	1,110	870	630	90	1,000,000	600	700	800	150	200	300
Cottonwood, common and black	600	650	800	1,130	930	730	530	80	900,000	450	550	700	100	125	150
Cypress, bald	900	1,100	1,300	1,840	1,520	1,190	870	100	1,400,000	800	1,000	1,100	225	250	350
Douglas fir (western Washington and Oregon)[d]	1,000	1,300	1,500	2,120	1,750	1,370	1,000	90	1,600,000	850	1,000	1,100	200	225	325
Douglas fir (Rocky Mountain type)[d]	700	900	1,100	1,500	1,280	1,010	730	85	1,200,000	700	800	800	200	225	275
Elm, cork	1,000	1,300	1,500	2,120	1,750	1,370	1,000	125	1,300,000	900	1,100	1,200	300	375	500
Elm, slippery and white	800	900	1,100	1,560	1,280	1,010	730	100	1,200,000	650	750	800	125	175	250
Fir, balsam	600	750	900	1,270	1,050	820	600	70	1,000,000	500	600	700	100	125	150
Fir, commercial white (white, noble, grand)	800	900	1,100	1,560	1,280	1,010	730	70	1,200,000	650	750	800	150	200	300
Gum, black and cotton	800	900	1,100	1,560	1,280	1,010	730	100	1,200,000	650	750	800	150	200	300
Gum, red	800	900	1,100	1,560	1,280	1,010	730	100	1,200,000	650	750	800	150	200	300
Hemlock, western	900	1,100	1,300	1,840	1,520	1,190	870	75	1,400,000	800	900	900	200	225	300
Hemlock, eastern	800	900	1,000	1,420	1,170	920	670	70	1,100,000	600	700	700	200	225	300
Hickory, true and pecan	1,200	1,500	1,900	2,690	2,220	1,740	1,270	140	1,800,000	1,000	1,200	1,500	350	400	600
Larch, western	900	1,100	1,200	1,700	1,400	1,100	800	100	1,300,000	800	1,000	1,100	200	275	325
Maple, sugar and black	1,000	1,300	1,500	2,120	1,750	1,370	1,000	150	1,600,000	900	1,100	1,200	300	375	500
Maple, red and silver	700	900	1,000	1,420	1,170	920	670	100	1,100,000	600	700	800	200	250	350
Oak, commercial red and white	1,000	1,200	1,400	1,980	1,630	1,280	930	125	1,500,000	800	900	1,000	300	375	500
Pine, southern yellow[d]	1,000	1,300	1,500	2,120	1,750	1,370	1,000	110	1,600,000	850	1,000	1,100	200	225	325
Pine, white, sugar, western white, western yellow	750	800	900	1,270	1,050	830	790	85	1,000,000	650	750	750	125	150	250
Pine, Norway	800	1,000	1,100	1,560	1,280	1,010	730	85	1,200,000	700	800	800	150	175	300
Poplar, yellow	800	900	1,000	1,420	1,170	920	670	80	1,100,000	600	700	800	125	150	250
Redwood	800	1,000	1,200	1,400	1,200	1,000	800	70	1,200,000	750	900	1,000	125	150	250
Spruce, red, white, Sitka	800	900	1,100	1,560	1,280	1,010	730	85	1,200,000	650	750	800	125	150	250
Spruce, Engelmann	500	650	750	1,060	880	690	500	70	800,000	450	550	600	100	140	175
Sycamore	800	900	1,100	1,560	1,280	1,010	730	80	1,200,000	650	750	800	150	200	300
Tamrack, eastern	900	1,100	1,200	1,700	1,400	1,100	800	95	1,300,000	800	900	1,000	200	225	300

[a] Working stresses for Extra Select (S1), Standard (S3), and Common (S4) grades are obtained by multiplying the basic stress by 7/6, 56, and 4/6, respectively, except in case of joints 4 in. thick and under in dry locations, stresses for which are given in the table.

[b] Values under modulus of elasticity are averages for species. For long columns a factor of 4 must be applied to them in order to obtain safe loads.

[c] The influence of knots on compressive strength of columns of constant cross section decreases as the length increases. When the length reaches 30 times the least dimension, knots such as are allowable in Select (S2) timbers have practically no effect on the strength as a column.

[d] The working stresses of any grade of timbers of Douglas fir and southern yellow pine, which meet the density requirements of the American Society for Testing Materials, may be increased one sixth of the allowable stress given in the table for basic or Select (S2) grade. Working stresses for any grade of Douglas fir, exclusive of Rocky Mountain type, and southern yellow pine, timbers not graded for density, but containing not less than six or more than twenty rings per inch measured over same portion of cross section as prescribed for density determinations may be increased one-fifteenth of basic stress.

Note: Stresses cannot be given for the grades of yard and dimension stock on account of manner in which the knots are limited on edges and narrow faces.

The standard S3 grade is in general more lenient for knots than the No. 1 common grade of yard dimension. This grade can, therefore, be selected from No. 1 and No. 2 common dimension. The same comparison holds between No. 2 common and the S4 grade.

U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin Project L-256 (Revised) November 9, 1923. Not for distribution.

ASTM D245–27

Table I.—Working stresses for joist & plank and beams & stringers[a]

Species	Extreme fiber in bending	Compression perpendicular to grain	Maximum horizontal shear	Modulus of elasticity
	Continuously dry (pounds per square inch)			
	Select Grade			
Cedar				
Western red	900	200	80	1,000,000
Northern and southern white	750	175	70	800,000
Port Orford	1,100	250	90	1,200,000
Alaska	1,100	250	90	1,200,000
Cypress				
Southern	1,300	350	100	1,200,000
Douglas Fir				
Coast Region				
Select	1,600	345	90	1,600,000
Dense Select	1,750	380	105	1,600,000
Rocky Mountain Region	1,100	275	85	1,200,000
Fir				
Balsam	900	150	70	1,000,000
Golden, noble, silver, white	1,100	300	70	1,100,000
Hemlock				
West Coast	1,300	300	75	1,400,000
Eastern	1,100	300	70	1,100,000
Larch				
Western	1,200	325	100	1,300,000
Oak				
Red and white	1,400	500	125	1,500,000
Pine				
Southern				
Select	1,600	345	110	1,600,000
Dense Select	1,750	380	128	1,600,000
California, Idaho and Northern white, Pondosa, sugar	900	250	85	1,000,000
Norway	1,100	300	85	1,200,000
Redwood	1,200	250	70	1,200,000
Spruce				
Red, white, Sitka	1,100	250	85	1,200,000
Englemann	750	175	70	800,000
Tamarack				
Eastern	1,200	300	95	1,300,000

Table I.—Working stresses for joist & plank and beams & stringers[a]—(*Continued*)

Occasionally wet but quickly dried (pounds per square inch)

Species	Extreme fiber in bending		Compression perpendicular to grain	Maximum horizontal shear	Modulus of elasticity
	4 in. and thinner	5 in. and thicker			
Select Grade					
Cedar					
Western red	710	800	150	80	1,000,000
Northern and southern white	580	—	140	70	800,000
Port Orford	890	1,000	200	90	1,200,000
Alaska	890	—	200	90	1,200,000
Cypress					
Southern	980	—	250	100	1,200,000
Douglas Fir					
Coast Region					
Select	1,240	1,385	240	90	1,600,000
Dense Select	1,370	1,515	265	105	1,600,000
Rocky Mountain Region	800	900	225	85	1,200,000
Fir					
Balsam	670	—	125	70	1,000,000
Golden, noble, silver, white	800	—	225	70	1,100,000
Hemlock					
West Coast	980	1,100	225	75	1,400,000
Eastern	800	—	225	70	1,100,000
Larch					
Western	980	1,100	225	100	1,300,000
Oak					
Red and white	1,070	1,200	375	125	1,500,000
Pine					
Southern					
Select	1,240	1,385	240	110	1,600,000
Dense Select	1,370	1,515	265	128	1,600,000
California, Idaho and Northern white, Pondosa, sugar	710	—	150	85	1,000,000
Norway	890	—	175	85	1,200,000
Redwood	890	1,000	150	70	1,200,000
Spruce					
Red, white, Sitka	800	900	150	85	1,200,000
Englemann	580	—	140	70	800,000
Tamarack					
Eastern	980	—	225	95	1,300,000

ASTM D245–27

Table I.—Working stresses for joist & plank and beams & stringers[a]—(*Continued*)

More or less continuously damp or wet (pounds per square inch)					
	Extreme fiber in bending		Compression perpendicular to grain	Maximum horizontal shear	Modulus of elasticity
Species	4 in. and thinner	5 in. and thicker			
Select Grade					
Cedar					
Western red	670	750	125	80	1,000,000
Northern and southern white	530	—	100	70	800,000
Port Orford	800	900	150	90	1,200,000
Alaska	800	—	150	90	1,200,000
Cypress					
Southern	800	—	225	100	1,200,000
Douglas Fir					
Coast Region					
Select	950	1,065	215	90	1,600,000
Dense Select	1,050	1,165	235	105	1,600,000
Rocky Mountain Region	620	700	200	85	1,200,000
Fir					
Balsam	530	—	100	70	1,000,000
Golden, noble, silver, white	710	—	200	70	1,100,000
Hemlock					
West Coast	800	900	200	75	1,400,000
Eastern	710	—	200	70	1,100,000
Larch					
Western	800	900	200	100	1,300,000
Oak					
Red and white	890	1,000	300	125	1,500,000
Pine					
Southern					
Select	950	1,065	215	110	1,600,000
Dense Select	1,050	1,165	235	128	1,600,000
California, Idaho and Northern white, Pondosa, sugar	670	—	125	85	1,000,000
Norway	710	—	150	85	1,200,000
Redwood	710	800	125	70	1,200,000
Spruce					
Red, white, Sitka	710	800	125	85	1,200,000
Englemann	440	—	100	70	800,000
Tamarack					
Eastern	800	—	200	95	1,300,000

[a] For material complying with structural grades of the American Society for Testing Materials. Values are those recommended by Forest Products Laboratory, U.S. Forest Service.

Appendix E—Dry-to-Green Ratios for U.S. Hardwood and Softwood

The tables in Appendix E provide dry-to-green ratios for clear wood properties of softwood and hardwood species grown in the United States, as specified in ASTM D2555, 1988 to current edition (2000).

Table E1—Dry-to-green ratios for U.S. softwood species

Species	MOR	MOE	UCS	Shear	C–perp
Baldcypress	1.60	1.22	1.78	1.23	1.81
Cedar					
Alaska	1.73	1.25	2.07	1.35	1.78
Atlantic white	1.44	1.24	1.97	1.16	1.67
Eastern red	1.25	1.36	1.69		1.32
Incense	1.28	1.24	1.65	1.05	1.59
Northern white	1.54	1.24	1.99	1.39	1.32
Port Orford	1.93	1.31	1.99	1.62	2.38
Western red	1.46	1.18	1.64	1.29	1.89
Douglas-fir					
Coast	1.62	1.25	1.91	1.25	2.08
Interior north	1.76	1.27	1.99	1.48	2.16
Interior south	1.75	1.28	2.00	1.59	2.20
Interior west	1.64	1.21	1.92	1.38	1.82
Fir					
Balsam	1.66	1.16	2.01	1.43	2.16
Calfornia red	1.81	1.28	1.98	1.36	1.82
Grand	1.53	1.26	1.80	1.22	1.85
Noble	1.74	1.25	2.03	1.31	1.90
Pacific silver	1.71	1.24	2.04	1.64	1.98
Subalpine	1.76	1.23	2.11	1.54	2.01
White	1.67	1.29	2.00	1.46	1.89
Hemlock					
Eastern	1.39	1.11	1.76	1.25	1.81
Mountain	1.83	1.28	2.24	1.65	2.32
Western	1.71	1.25	2.14	1.49	1.94
Larch, western	1.70	1.28	2.03	1.56	2.32
Pine					
Eastern white	1.74	1.24	1.97	1.33	2.01
Jack	1.64	1.27	1.92	1.55	1.95
Lodgepole	1.70	1.24	2.06	1.28	2.41
Monterey	2.00	1.27	2.22	1.69	2.11
Ponderosa	1.84	1.30	2.17	1.61	2.05
Red	1.88	1.27	2.22	1.77	2.31
Sugar	1.67	1.16	1.81	1.58	2.32
Western white	2.06	1.22	2.07	1.54	2.45
Loblolly	1.75	1.28	2.03	1.61	2.04
Longleaf	1.70	1.25	1.96	1.45	2.01
Pitch	1.59	1.19	2.01	1.58	2.23
Pond	1.56	1.37	2.06	1.48	2.06
Sand	1.54	1.38	2.01	0.96	1.86
Shortleaf	1.76	1.26	2.06	1.54	2.31
Slash	1.87	1.29	2.13	1.74	1.93
Spruce	1.73	1.23	1.99	1.66	2.63
Virginia	1.77	1.25	1.96	1.52	2.32
Redwood	1.34	1.15	1.68	1.25	1.93
Spruce					
Black	1.77	1.16	2.10	1.67	2.27
Engelmann	1.98	1.26	2.06	1.89	2.06
Red	1.80	1.25	2.04	1.71	2.09
Sitka	1.81	1.27	2.10	1.51	2.07
White	1.89	1.25	2.20	1.53	2.06
Tamarack	1.62	1.33	2.06	1.49	2.07
Average	1.69	1.25	1.99	1.47	2.03
Minimum	1.25	1.11	1.64	0.96	1.32
Maximum	2.06	1.38	2.24	1.89	2.63
5th percentile	1.30	1.15	1.66	1.09	1.42

Table E2—Dry-to-green ratios for U.S. hardwood species

Species or Region	MOR	MOE	UCS	Shear	C–perp
Alder, red	1.50	1.18	1.97	1.40	1.73
Ash					
Black	2.10	1.53	2.60	1.82	2.20
Green	1.49	1.18	1.69	1.52	1.78
Oregon	1.67	1.20	1.72	1.50	2.36
White	1.57	1.21	1.86	1.41	1.73
Aspen					
Bigtooth	1.68	1.27	2.12	1.48	2.19
Quaking	1.64	1.37	1.99	1.30	2.04
Basswood, American	1.76	1.41	2.13	1.65	2.16
Beech, American	1.74	1.25	2.06	1.56	1.86
Birch					
Paper or white	1.92	1.36	2.41	1.45	2.20
Yellow	2.01	1.34	2.42	1.70	2.26
Sweet	1.80	1.32	2.28	1.80	2.29
Butternut	1.51	1.21	2.11	1.55	2.08
Cherry, black	1.54	1.14	2.01	1.51	1.91
Chestnut, American	1.53	1.32	2.15	1.36	2.00
Cottonwood					
Black	1.73	1.18	2.05	1.69	1.82
Eastern	1.62	1.35	2.15	1.36	1.95
Elm					
American	1.65	1.20	1.90	1.51	1.95
Cedar	1.47	1.27	1.61	1.70	1.57
Rock	1.56	1.29	1.87	1.51	2.02
Slippery	1.62	1.21	1.92	1.48	1.97
Winged	1.61	1.36	1.83	1.82	1.61
Hackberry	1.70	1.25	2.05	1.49	2.23
Hickory					
Bitternut	1.66	1.28	1.98	1.58	2.10
Mockernut	1.74	1.41	2.00	1.36	2.13
Nutmeg	1.83	1.32	1.74	1.79	2.06
Pecan	1.40	1.26	1.97	1.40	2.22
Pignut	1.71	1.37	1.91	1.57	2.15
Shagbark	1.83	1.38	2.01	1.60	2.08
Shellbark	1.72	1.41	2.04	1.78	2.23
Water	1.65	1.30	1.85		1.75
Honeylocust	1.44	1.27	1.70	1.36	1.60
Locust, black	1.40	1.11	1.50	1.41	1.58

Species or region	MOR	MOE	UCS	Shear	C–perp
Magnolia					
Cucumbertree	1.66	1.16	2.01	1.35	1.74
Southern	1.66	1.27	2.02	1.47	1.86
Maple					
Bigleaf	1.45	1.32	1.84	1.56	1.68
Black	1.68	1.22	2.04	1.61	1.69
Red	1.75	1.19	1.99	1.61	2.48
Silver	1.53	1.21	2.10	1.41	2.00
Sugar	1.67	1.18	1.95	1.59	2.27
Oak					
Red oak					
Black oak	1.69	1.39	1.88	1.56	1.32
Cherrybark	1.67	1.27	1.89	1.51	1.63
Laurel	1.59	1.21	2.20	1.55	1.85
Northern red	1.72	1.35	1.97	1.46	1.65
Pin	1.69	1.31	1.85	1.61	1.42
Scarlet	1.67	1.30	2.04	1.34	1.34
Southern red	1.58	1.31	2.01	1.49	1.60
Water	1.72	1.30	1.81	1.63	1.65
Willow	1.96	1.48	2.35	1.40	1.85
White oak					
Bur	1.43	1.18	1.84	1.35	1.78
Chestnut	1.65	1.16	1.94	1.23	1.58
Live	1.54	1.25	1.64	1.20	1.39
Overcup	1.57	1.24	1.84	1.52	1.50
Post	1.63	1.39	1.90	1.44	1.67
Swamp chestnut	1.64	1.31	2.05	1.58	1.93
Swamp white	1.80	1.28	1.97	1.54	1.56
White	1.83	1.43	2.09	1.60	1.59
Poplar, balsam	1.76	1.47	2.38	1.57	2.18
Sweetgum	1.76	1.37	2.08	1.61	1.70
Sycamore, American	1.55	1.33	1.84	1.47	1.91
Tupelo					
Black, black gum	1.36	1.16	1.82	1.22	1.92
Water	1.32	1.19	1.76	1.33	1.81
Walnut, black	1.54	1.18	1.76	1.13	2.08
Yellow-poplar	1.70	1.29	2.08	1.50	1.85
Average	1.65	1.28	1.98	1.51	1.88
Minimum	1.40	1.11	1.50	1.30	1.32
Maximum	2.10	1.53	2.60	1.82	2.48
5th percentile	1.40	1.16	1.65	1.22	1.40

Appendix F—Derivation of Moisture Content–Property Adjustment Models for D1990–91

Basic Model

The simplified model was developed from the linear surface models, which start with the assumption that the strength of a specimen is a linear function of its moisture content:

$$P = b_0 + b_1 M$$

Thus, in going from moisture content M_1 with strength S_1 to moisture content M_2, the resulting strength is

$$P_2 = P_1 + b_1(M_2 - M_1) \qquad \text{(F1)}$$

To use the model, one must be able to predict b_1. The three methods considered were to use a linear, quadratic, or cubic function of the strength property at 15% moisture content to predict b_1; that is,

1. $b_1 = C_0 + C_1 P_{15}$
2. $b_1 = C_0 + C_1 P_{15} + C_2 P_{15}^2$
3. $b_1 = C_0 + C_1 P_{15} + C_2 P_{15}^2 + C_3 P_{15}^3$

P_{15} is obtained by finding the strength at 15% moisture content that when adjusted to moisture content M_1 gives strength P_1. From Equation (F1), this means solving

$$P_1 = P_{15} + b_1(M_1 - 15) \qquad \text{(F2)}$$

This process is complicated by the fact that b_1 is a function of P_{15} (option 1, 2, or 3). When option 3 is used, the roots of a cubic equation must be solved to get P_{15}. It is possible to solve this equation in closed form, but the equation would be so messy that no one would use it. Thus, a computer program is the only viable solution for option 3. Both options 1 and 2 are more tractable to a closed-form solution.

Simplified Model

Because all three linear surface models perform relatively the same, a simplified model could be developed. Consider the linear surface model with option 1. In this case, we can substitute for b_1 in Equation (F2) using option 1; that is,

$$P_1 = P_{15} + (C_0 + C_1 P_{15})(M_1 - 15)$$

which implies

$$P_{15} = \left[\frac{P_1 + C_0(15 - M_1)}{1 + C_1(M_1 - 15)}\right]$$

Combining this equation with Equation (F1) and option 1 gives

$$P_2 = P_1 + \left[C_0 + C_1 \frac{P_1 + C_0(15 - M_1)}{1 + C_1(M_1 - 15)}\right](M_2 - M_1)$$

which can be rewritten as

$$P_2 = P_1 + \left\{\frac{(C_0/C_1) + P_1}{[(1 - C_1 15)/C_1] + M_1}\right\}(M_2 - M_1)$$

The coefficients of this equation are obtained from the moisture content data and are as follows:

	Bending	Tension
C_0	100.93534538	48.15270011
C_1	–0.04179655	–0.01541423

Thus, for bending the equation becomes

$$P_2 = P_1 + [(P_1 - 2414.92)/(38.93 - M_1)](M_1 - M_2)$$

and for tension,

$$P_2 = P_1 + [(P_1 - 3123.91)/(79.88 - M_1)](M_1 - M_2)$$

For simplicity,

$P_2 = P_1 + [(P_1 - 2415)/(40 - M_1)](M_1 - M_2)$ for bending

$P_2 = P_1 + [(P_1 - 3150)/(80 - M_1)](M_1 - M_2)$ for tension

To prevent the model from showing a decrease in strength as moisture content drops, it was decided to take no change below 2,415 lb/in^2 in bending and 3,150 lb/in^2 in tension.

Normalization

As discussed for MOR, normalization is an option that will allow the properties of a lower strength species to be scaled relative to those of Douglas Fir and Southern Pine prior to adjusting their strength to a common moisture content level. The concern was that without some type of adjustment, a significant portion of the distribution of a much weaker species might fall below the lower limit of the stronger species where the species showed no change in strength with change in moisture content. Normalization was an attempt to fit the data to the model so that the weaker species had the same percentage of the lower tail below the lower cut-off as the percentage for the stronger species used to formulate the model. To "normalize," the data are first adjusted to 15% moisture content and the mean of the 2 by 4 Select Structural values at 15% is calculated. The data at the original moisture content is then adjusted to "fit" the model using

$$P_1^* = [(P_1 - C)(A/B)] + C$$

where

A is the mean property of 2 by 4 Select Structural 15% moisture content values of the species used to create the model (lb/in^2),

B the mean property of 2 by 4 Select Structural 15% moisture content values of the species being adjusted (lb/in^2), and

C a constant (lb/in^2).

This “adjusted property value” P_1^* at the original moisture content M_1 is then modified to an “adjusted property value” P_2^* at 15% moisture content using the standard procedure. This “adjusted property value” P_2^* must then be “unadjusted” or scaled back to its original scale using

$$P_2 = [(P_2^* - C)(B/A)] + C$$

where *A* and *C* are the following for MOR, UTS, and UCS:

	A	*C*
MOR	10,120	1,000
UTS	7,452	0
UCS	5,785	0

In practice, normalization has been found to have little effect on allowable property estimates.

Wet Use Factors

The factors in Table 9 of the text are based on the change in capacities of lumber with moisture content relative to a 15% moisture content base. The factors selected provide acceptable estimates in the range of allowable property values normally assigned for lumber design (that is, 5th percentile strength levels, not necessarily strength values throughout the strength distribution). Changes in property values with change in moisture content were calculated using a property adjustment model, and dimensional changes were calculated using the equations of Appendix X1 of ASTM D1990–91 (see also Green 1989).

In some earlier drafts of D1990 that were balloted in Committee D7, the quadratic surface model of Green and Evans (1989) (see computer programs of Evans and others 2000) were used to develop the wet use factors relative to a base of 12% moisture content. These capacities by this approach are shown in Table F1, where the strength properties are given in terms of characteristic values. The wet use factors using this approach differed from those of Table 9 only in the factor for F_c (UCS in Table F1), which was judged to be 0.7 for F_c values $\geq$ 750 lb/in^2.

As previously noted, concerns developed during the ASTM balloting process about the complexity of the quadratic surface model. This led to adoption of the simplified version, the linear surface model (Eq. (3) in the text), which is applicable only to the lower tails of strength distributions. During the balloting process, the basis for the wet use factors was also changed from 12% to 15% moisture content. Table F2 reproduces the capacities given in Annex X10 of D1990–91. These capacities formed the bases for the judgments that led to the wet use factors of Table 9. Note that the properties of Table F2 are shown as the characteristic values divided by the general adjustment factors (e.g., F_b = MOR/2.1).

Table F1—Relative capacity of lumber at three moisture content (MC) levels based on quadratic surface model for adjusting lumber properties (Evans and others 2000) and shrinkage formulas given in ASTM D1990–91

		Ratio of property to property at 12% MC				Ratio of dimensions to dimensions at 12% MC			Ratio of capacity to capacity at 12% MC		
Property	Value at 12% MC	12% MC	15% MC	23% MC	Comparative section	12% MC	15% MC	23% MC	12% MC	15% MC	23% MC
MOR	1000	1.00	0.993	0.973	Section modulus (*Z*)	1.00	1.019	1.071	1.00	1.012	1.042
	2000	1.00	1.024	0.920		1.00	1.019	1.071	1.00	1.043	0.985
	3000	1.00	1.031	0.844		1.00	1.019	1.071	1.00	1.051	0.904
	4000	1.00	1.019	0.796		1.00	1.019	1.071	1.00	1.038	0.852
	5000	1.00	1.002	0.762		1.00	1.019	1.071	1.00	1.021	0.816
UTS	500	1.00	1.062	1.164	Area (*A*)	1.00	1.012	1.045	1.00	1.075	1.217
	1000	1.00	1.073	1.128		1.00	1.012	1.045	1.00	1.086	1.179
	1500	1.00	1.085	1.057		1.00	1.012	1.045	1.00	1.098	1.105
	2000	1.00	1.081	1.017		1.00	1.012	1.045	1.00	1.094	1.063
	2500	1.00	1.072	0.989		1.00	1.012	1.045	1.00	1.085	1.034
	3000	1.00	1.062	0.968		1.00	1.012	1.045	1.00	1.075	1.012
	3500	1.00	1.052	0.951		1.00	1.012	1.045	1.00	1.065	0.994
	4000	1.00	1.042	0.937		1.00	1.012	1.045	1.00	1.055	0.979
	4500	1.00	1.033	0.924		1.00	1.012	1.045	1.00	1.046	0.966
	5000	1.00	1.026	0.914		1.00	1.012	1.045	1.00	1.038	0.955
UCS	500	1.00	0.974	0.768	Area (*A*)	1.00	1.012	1.045	1.00	0.986	0.803
	1000	1.00	0.974	0.768		1.00	1.012	1.045	1.00	0.986	0.803
	1500	1.00	0.974	0.768		1.00	1.012	1.045	1.00	0.986	0.803
	2000	1.00	0.974	0.768		1.00	1.012	1.045	1.00	0.986	0.803
	2500	1.00	0.974	0.768		1.00	1.012	1.045	1.00	0.986	0.803
	3000	1.00	0.949	0.732		1.00	1.012	1.045	1.00	0.961	0.765
	3500	1.00	0.927	0.700		1.00	1.012	1.045	1.00	0.938	0.732
	4000	1.00	0.909	0.674		1.00	1.012	1.045	1.00	0.920	0.705
MOE	0.5	1.00	0.954	0.834	Moment of inertia (*I*)	1.00	1.026	1.097	1.00	0.978	0.915
	1.0	1.00	0.955	0.834		1.00	1.026	1.097	1.00	0.979	0.915
	1.5	1.00	0.955	0.834		1.00	1.026	1.097	1.00	0.979	0.915
	2.0	1.00	0.955	0.834		1.00	1.026	1.097	1.00	0.979	0.915
	2.5	1.00	0.955	0.834		1.00	1.026	1.097	1.00	0.979	0.915

Table F2—Relative capacity of lumber at three moisture content (MC) levels based on simplified surface model for adjusting lumber properties (Eq. (3), Evans and others 2000) and shrinkage formulas given in ASTM D1990–91

Property	Value at 15% MC	Ratio of property to property at 15% MC			Comparative section	Ratio of dimensions to dimensions at 15% MC			Ratio of capacity to capacity at 15% MC		
		10% MC	12% MC	23% MC		10% MC	12% MC	23% MC	10% MC	12% MC	23% MC
F_b	1000	1.000	1.000	1.000	Section modulus (*Z*)	0.978	0.987	1.036	0.978	0.987	1.036
	2000	1.085	1.051	0.864		0.978	0.987	1.036	1.061	1.037	0.895
	3000	1.123	1.074	0.803		0.978	0.987	1.036	1.099	1.060	0.831
	4000	1.143	1.086	0.772		0.978	0.987	1.036	1.117	1.071	0.800
	5000	1.154	1.092	0.754		0.978	0.987	1.036	1.129	1.078	0.781
F_t	500	1.000	1.000	1.000	Area (*A*)	0.979	0.988	1.033	0.979	0.988	1.033
	1000	1.000	1.000	1.000		0.979	0.988	1.033	0.979	0.988	1.033
	1500	1.000	1.000	1.000		0.979	0.988	1.033	0.979	0.988	1.033
	2000	1.019	1.012	0.969		0.979	0.988	1.033	0.998	0.999	1.002
	2500	1.031	1.018	0.951		0.979	0.988	1.033	1.010	1.006	0.983
	3000	1.038	1.023	0.938		0.979	0.988	1.033	1.017	1.010	0.970
	3500	1.044	1.026	0.930		0.979	0.988	1.033	1.023	1.014	0.961
	4000	1.048	1.029	0.923		0.979	0.988	1.033	1.027	1.016	0.954
F_c	500	1.000	1.000	1.000	Area (*A*)	0.979	0.988	1.033	0.979	0.988	1.033
	1000	1.069	1.042	0.889		0.979	0.988	1.033	1.047	1.029	0.919
	1500	1.134	1.080	0.786		0.979	0.988	1.033	1.111	1.067	0.812
	2000	1.166	1.100	0.734		0.979	0.988	1.033	1.142	1.086	0.759
	2500	1.186	1.111	0.703		0.979	0.988	1.033	1.161	1.098	0.727
	3000	1.179	1.119	0.682		0.979	0.988	1.033	1.174	1.105	0.705
	4000	1.215	1.129	0.657		0.979	0.988	1.033	1.190	1.115	0.678
MOE	0.5	1.079	1.047	0.874	Moment of inertia (*I*)	0.967	0.980	1.054	1.044	1.027	0.921
	1.0	1.079	1.047	0.874		0.967	0.980	1.054	1.044	1.027	0.921
	1.5	1.079	1.047	0.874		0.967	0.980	1.054	1.044	1.027	0.921
	2.0	1.079	1.047	0.874		0.967	0.980	1.054	1.044	1.027	0.921
	2.5	1.079	1.047	0.874		0.967	0.980	1.054	1.044	1.027	0.921

Appendix G—Research on Effect of Moisture Content on Compression Perpendicular to Grain

1949 to 1957

ASTM D245–49T states that “modifications for seasoning in compression perpendicular to the grain are now under study at the U.S. Forest Products Laboratory.” Some studies in the period 1949 to 1957 were found in published and unpublished research files at the Forest Products Laboratory. However, it is unclear to what extent this research led to the recommendation given in D245–57T (paragraph 61f) that “working stresses in compression perpendicular to the grain may be increased by 50 per cent above the values given in Table VIII (a table of basic stresses) for lumber that will be continuously dry in use.”

One of the most prominent studies in this period was that of Dr. Robert Youngs on the perpendicular-to-grain properties of red oak (Youngs 1957). Compression perpendicular-to-grain specimens were obtained using a 4 × 3 ×4 factorial design (4 logs, 3 temperatures, and 4 moisture content levels). The target moisture content levels chosen were 6%, 12%, and 18%, as well as green, and temperatures were 80°F, 130°F, and 180°F. The tests were conducted on 0.5- by 0.5- by 2-in.- long specimens, with the load applied tangential to the growth increments. Eight specimens were used per treatment condition (two specimens per log). Both proportional limit stress and stress at 2.5% strain were calculated (Table G1). The change in proportional limit stress was found to be less than that of the stress at 2.5% strain, but the change in both stresses was a function of the degree of dryness. At 80°F, the change in stress at 2.5% strain of dry oak was plotted relative to the stress at 2.5% stain for green oak (Fig. G1). The relationship continued to increase from green to about 5.5% moisture content. At 12% moisture content, the dry stress was about 60% higher than that for green oak.

Unpublished records also indicate that a second study was begun on the perpendicular-to-grain properties of ponderosa pine. Apparently, the intent of the study was to virtually repeat Young’s experiments, but with a softwood species. Although several researchers worked on this problem over the years, the study was never completed. The portion dealing with the effect of moisture content and the reversible effect of temperature on compression perpendicular to grain was completed but never published. These results show a much larger percentage of change in compression perpendicular to grain with drying than did the oak study (Fig. G1). At 12% moisture content, the increase in stress was about 100% that of the green wood.

A study on American beech was also published during this period (Ellwood 1954). Logs obtained from six locations in the eastern United States were cut into 0.5- by 0.5- by 2-in.-long specimens. Specimens were tested green or after conditioning to moisture contents of 6%, 12%, and 18%. Tests were conducted at 80°F, 100°F, 120°F, 140°F, and 160°F. Specimens were tested parallel to growth increments. The stress proportional limit and at 2.5% stain were calculated (Table G1). The percentage of change in stress at 2.5% strain for dry beech, relative to that for green lumber, is plotted in Figure G1. At 12% moisture content, the increase in compression perpendicular to grain was about 85%.

Table G1—Results of compression perpendicular to grain of northern red oak and American beech[a]

Species	Moisture content (%)	Stress (lb/in^2) at		Percentage of change due to seasoning[b]	
		Proportional limit	2.5% strain	Proportional limit	2.5% strain
Northern red oak[c]	6	806	1,504	75.2	110
	12	574	1,130	24.7	75.1
	18	383	765	–16.7	6.8
	green	460	716	0	0
American beech[d]	6	1,045	1,773	135	135
	12	780	1,402	75.7	86.2
	18	583	989	31.3	31.4
	green	444	753	0	0

[a] Tests were conducted at 0° angle to growth rings at 80°F.

[b] Percentage of change calculated as 100 (dry – green)/green.

[c] Youngs 1957.

[d] Ellwood 1954.

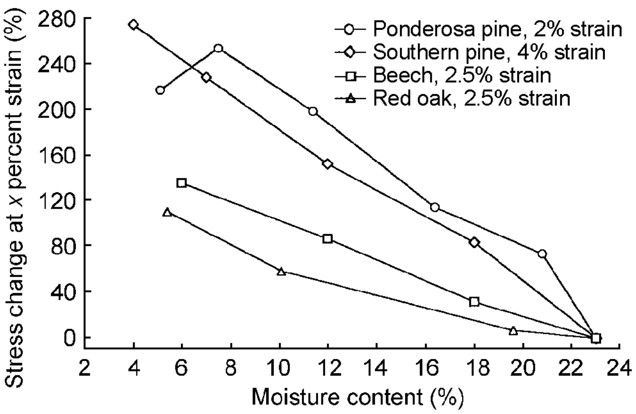

Figure G1—Effect of moisture content on compressive stress perpendicular to grain at 80°F, relative to green values. Data sources: ponderosa pine, Forest Products Laboratory unpublished data; Southern Pine, Green and Kretschmann 1994; beech, Ellwood 1954; red oak, Youngs 1957.

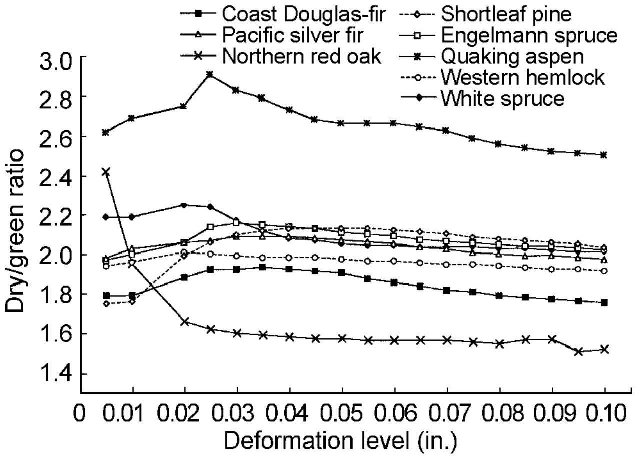

Figure G2—Dry/green ratios for compressive stress perpendicular to grain of eight species (adapted from Bendtsen and Galligan 1979).

Later Research

In the research discussed in the text, results were presented for only two deformation levels: proportional limit and stress at approximately 2.5% strain. Research Paper 337 (Bendtsen and Galligan 1979) compares ratios of stress for green lumber and lumber with 12% moisture content at 20 levels of strain for eight hardwood and softwood species (Fig. G2). For most species, the ratio stabilized for deformation levels over approximately 0.02 to 0.03 in. Because all test specimens were standard 2 by 2 in. in cross section, the change was stable for stresses past approximately 1.0% to 1.5% strain.

Green and Kretschmann (1994) studied the properties of clear Southern Pine as a function of moisture content from green to 4% moisture content. At 4% strain, the change in stress increased continuously with decreasing moisture content (Fig. G1). At 12% moisture content, the change in stress was about 150% that of green wood.

This page revised May 2002

Appendix H—Potential Source of Dry-Green Ratio for Shear in ASTM D245

ASTM D245–98 permits allowable shear values of dimension lumber to be increased 13% for lumber with maximum moisture content of 15%. As discussed in the text, this factor apparently originated in 1934 with a 9/8 factor developed from information in Misc. Pub. 185. In ASTM D2555, the dry-green ratio obtained by block shear tests (ASTM D143–94) on small clear specimens averages about 2.0 for softwood species and about 1.9 for hardwood species (App. E, Table E1). If block shear tests were the basis for moisture adjustments in Misc. Pub. 185, why was the factor (dry-green ratio) only 1.125? One potential explanation is that this low ratio is based not on clear wood tests but on observations from tests of full-size beams that failed in shear. We have found no direct evidence of this assumption, but it is supported by the following concepts:

1. Original allowable shear stresses were really “calibrated” to bending members that failed in shear.

2. Initial seasoning increases in extreme fiber in bending for dry dimension lumber were based on test results from full-size members, not on clear wood data.

Calibration of Allowable Shear Stresses

In an unpublished letter to Alex R. Entrican in 1933, John Newlin explains some of the reasoning behind the derivation of working properties in the United States:

> Our assigned stresses in horizontal shear are primarily the results of tests of structural timbers. A part of these bending tests were made on short, high stringers with symmetrical loads placed three to four times the height of the beams from the support.

Here we should point out that Newlin is not talking about some special series of beam shear tests, but rather inferences made from the standard bending tests at the time on timbers. Since 1906, the standard test conducted by the Forest Service had used a simply supported beam with symmetric loads placed at one-third points of the span. However, the standard span was approximately 15 ft, regardless of the depth of the beam. Thus, the standard test provided an “a/h” ratio between 3 and 4. Moreover, prior to 1906, the standard test was conducted using a 15-ft span, but with a single load applied in the center of the span.

Newlin is thus indicating that allowable properties for shear were determined from an evaluation of failure stresses for beams that first failed in shear. Given this fact, it seems plausible that moisture adjustments might also be based on observations of full-size tests.

Tests of Full-Size Members as Basis for Adjustments

As was discussed in the text for MOR, the “25% rule” first discussed in the unpublished memorandum of 1924 by Newlin and Johnson was based on test results for graded lumber tested green and dry. In this instance, the resulting moisture content adjustments for dimension lumber were also much lower than those found from tests of small clear specimens. Thus, the idea of basing property–moisture content adjustments on results from tests of full-size specimens would not have been novel in 1934.

One source of information that was available in 1933 was the data summarized in Bulletin 108 (Cline and Heim 1912). However, despite the large numbers of timbers tested, in very few timbers was the first failure judged to be due to shear (or occurring at checks and splits). Another problem is that the range of moisture contents of beams considered green sometimes overlapped with the range of moisture contents of beams considered dry. Also, there is no assurance that the beams that failed in shear were of equal quality in the green and dry groups. These were the data used to develop the initial grading system proposed by the Forest Products Laboratory, and specimens were therefore not selected on the basis of “grade.” However, the data published in Bulletin 108 were the primary data that would have been available to Newlin and Johnson, and thus it is instructive to look at what they may have evaluated.

Two of the largest data sets within the various species and beam sizes reported in Bulletin 108 are the green and dry bending data from tests on Douglas Fir–Larch and Southern Pine 6- by 16-in. timbers. Using the data from only those beams identified as having initial failure in shear, we calculated the shear stress at time of failure using the VQ/IT concept. Average values from these calculations are summarized in Table H1. For Douglas Fir–Larch, the dry-green ratio is 1.32; for Southern Pine, the ratio is only 0.96. For both species groups, the average moisture content of the dry group was only approximately 20%. Thus, these two sets of results are contradictory. From the information available, it is not possible to further investigate reasons for the difference in performance. However, a limited amount of other timber data that are not part of Bulletin 108 are available that can shed additional light on dry and green beam shear failures.

In 1931, Markwardt published results from tests on 8- by 16-in. western hemlock and Sitka spruce timbers sampled in Alaska. Markwardt carefully selected 32-ft-long logs of approximately uniform quality along their length. Each log was cut in half and one-half tested green. The other half was carefully air dried under cover for a long time before testing. Testing was conducted over a 15-ft span with loads at the one-third point of the span. Because only one green Sitka spruce beam failed in shear, those results are not useful.

Table H1—Effect of moisture content on calculated shear strength at failure of timbers judged to have failed initially in shear[a]

		Green lumber			Dry lumber			
Load point and species group	Ref[b]	*n*	MC (%)	Shear	*n*	MC (%)	Shear	Dry-green ratio
One-third-point load								
Douglas Fir	(1)	7	46	287	15	20	380	1.32
Southern Pine	(1)	13	33	362	9	20	348	0.96
Western Hemlock	(2)	5	42	281	18	17	394	1.40
Center-point load								
Douglas Fir	(3)	3	?	166	5	?	211	1.33
Southern Pine	(4)	12	51	375	12	20	493	1.31[c]
					4	23	364	0.97[d]

[a] Timbers were 8 by 16 in.

[b] References: (1) Cline and Heim 1912, (2) Markwardt 1931, (3) Cline and Knapp 1911, and (4) Betts 1909.

[c] Air dried under shelter for 21 months

[d] Air dried in the open for 3.5 months.

The average dry-green ratio for western hemlock judged to have failed in shear was 1.4 (Table H1).

As part of a study on Douglas-fir timber properties, Cline and Knapp (1911) used a simply supported beam loaded by a single load at mid-span, the older Division of Forestry procedure. Study material consisted of 171 green beams and 81 “air dry” beams (no moisture content given). No attempt was made to match quality of green and dry timbers. Three green beams and five air-dry beams failed in shear. The dry-green ratio of these members was 1.33 (Table H1).

Finally, Betts (1909) evaluated failures in center-point-loaded Southern Pine 8- by 16-in. beams for green and two dry exposure conditions. Again, timber groups were not matched for quality. For beams dried outdoors under shelter for 21 months, the dry-green ratio based on calculated shear stress at time of failure was 1.31; for beams dried in the open for 3.5 months, the dry-green ratio was 0.97 (Table H1).

These studies suggest that the shear strength of carefully dried beams might increase about 30% when the beams are dried to an average moisture content of about 20%. However, the data also support the judgment given in Circular 295 that excessive checking, which can occur when green beams dry quickly, may result in much lower values. This type of reasoning could have resulted in the adoption of the more conservative 9/8 factor. It is also interesting to note that for softwoods, a factor of 1.125 (later rounded to 1.13) is not far from the 5th percentile dry-green ratio tabulated in D2555 (App. E).

Appendix I—Profiles of Early Pioneers

Early pioneers had a tough job: to devise the first national consensus system for grading and property assignments in the United States. Later contributions may have been just as sweeping, but these were changes to an existing policy. The following individuals each contributed to the first set of procedures for adjusting lumber properties for change in moisture content. For all of them, this was but one of many contributions to wood engineering.

Walter Gilman Berg (1858–1908)

Walter G. Berg was born in the United States, but received most of his education in Europe. At university, Berg was awarded a Gold Medal by the King of Wurtemberg for a treatise on spherical conic sections. In recognition of this award, the Polytechnic Institute of Stuttgart awarded Berg a scholarship and employed him for government surveys. In 1878, Berg received a Civil Engineer degree from the Institute.

Berg returned to the United States in 1879 and entered a career with the railroads. His first job was office assistant and shop inspector of railroad bridges of the Delaware Bridge Company. In 1880, he joined the engineering department of the Richmond and Allegheny Railroad; in 1882, he became principal assistant engineer of the East Tennessee, Virginia, and Georgia Railroad; and in 1883, he joined the Lehigh Valley Railroad Company where he was to spend the rest of his career.

At Lehigh Valley, Berg was initially in charge of design and construction of shop buildings and roundhouses. In 1886, he designed and constructed a creosote treatment plant at Perth Amboy, New Jersey, and was put in charge of the operation. This plant was among the earliest of its kind to be operated by an American railroad. By 1890, Berg had become chief engineer.

Berg was very active in a number of professional organizations and served as president of the Association of Railway Superintendents of Bridges and Buildings and of the American Railway Engineering and Maintenance of Way Association. For his engineering standing and prominence he was selected to serve on the jury of awards on railroad exhibits at the St. Louis World Fair in 1904. In 1908, he was appointed a delegate to the conference on conservation of natural resources held by President Theodore Roosevelt. Berg died suddenly on May 12, 1908.

Berg authored many books and publications. The recommendations of the committee (App. A) that he chaired on the strength of bridge and trestle timbers, presented in New Orleans in 1895, is discussed in the committee's report on the early development of standardized procedures (Berg and others 1907). This report contained a comprehensive review of the available test data on wood properties by the leading authorities of the day. It also included recommendations on specific design concerns such as bolted connections and column design. The report was published in whole or part by a number of technical outlets, including incorporation in the appendix of *Economical Designing of Timber Trestle Bridges* by A. L. Johnson (1902). Because of the demand for this information, in 1899 Berg also published the report as *Berg's Complete Timber Test Record* (B. S. Wasson and Co., Chicago, IL). We found it easier to obtain a copy of the original committee report than Berg's *Test Record*. The *Test Record* differs from the committee's report by the addition of six pages, which discuss the distribution of the committee's report and list publications since October 1895. The *Test Record* also includes an interesting diagram prepared by Berg of test data on full-size "yellow pine" columns and formulas for column strength.

Harry D.Tiemann (1875–1966)

Dr. Harry Tiemann was born in Brooklyn, New York, on March 26, 1875. The son of a Civil War veteran and chemist, he completed his engineering degree from Steven's Institute of Technology in 1897 and a master of forestry degree from Yale in 1903. In 1900, Tiemann was hired by the Division of Forestry to conduct research on wood moisture relationships at the new testing laboratory established at Yale University. He conducted an extensive and exhaustive study of the effect of moisture content on the physical and mechanical properties of clear wood. Even if he had done nothing else of note in his professional career, Harry Tiemann would be remembered as the first to articulate the concept of the "fiber saturation point" (Tiemann 1906). In 1903, he became head of the New Haven laboratory, a post he held for 6 years. He spent the winter of 1909 in Washington, D.C., perfecting his design for a water spray dry kiln and obtaining a patent. In the spring of 1910, Tiemann came to the new Forest Products Laboratory (FPL) in Madison, Wisconsin, and remained there until 1945.

In honor of Tiemann, a Douglas-fir tree was planted and a memorial plaque placed at FPL in May 1976. In an article in the FPL newsletter *Chips* following the dedication ceremony, FPL scientist Bill Feist wrote of Tiemann's accomplishments:

> During World War I, he developed the first practical wood drying kiln used in this country. His water-spray kiln saved the United States from what might have been a disastrous shortage of seasoned wood during the war. During the war, 300 of these kilns were built to dry everything from gunstocks to airplane wing beams. His kilns were the only ones officially accepted by the War Department for the drying of war materials. He was the chief of FPL's first Timber Physics section, and retired in 1945. When he died in 1966, he was survived by a son, Dr. Theodore D. Tiemann, Professor of Metallurgical and Mining Engineering at the University of Wisconsin, Madison. At that time, as is still true, this

> engineering department occupied the original Forest Products Laboratory building on University Avenue.

John A. Newlin (1872–1943)

John Newlin was born February 2, 1872, in Plainfield, Indiana. He graduated from Purdue University with a bachelor of science degree in civil engineering. For 4 years, Newlin served as a civil engineer with the Chicago, Indianapolis, and Louisville Railroad and the Pittsburgh, Cincinnati, Chicago, and St. Louis Railroad. In 1904, he joined the USDA Division of Forestry as an engineer in timber testing on a cooperative project then under way with Purdue University. A short time later he was placed in full charge of this work, which was shifted to Madison in 1910.

Newlin was chief of the Timber Mechanics Division at FPL from 1910 to 1939, when he was relieved of administrative duties so that he could devote full time to research and consultation. He died March 27, 1943, 4 weeks after his retirement. The following is an excerpt from a profile written by L. J. Markwardt:

> John A. Newlin was the first Chief of the Division of Timber Tests, later named Timber Mechanics, and then Wood Engineering. He was transferred from Purdue University when the Laboratory was organized, where he worked on Forest Service projects under Dr. William Hendrick Hatt, Dean of Engineering.
>
> In my first FPL appointment in September 1912 as Assistant Engineer, I assumed duties as Assistant Chief of the Division, and worked under Newlin until his retirement [from Administration] in the 1930s, when I was appointed Chief to succeed him. I thus had a long tenure with Newlin, and probably knew him as well or better than anyone else.
>
> Newlin was both competent and modest. He thrived on details of technical analysis, and had an uncanny ability to develop sound conclusions from seemingly conflicting data. He could clearly visualize the distribution of strain in members under stress, which led to refinements and modifications of the usual formulas used in stress analysis. This was his preferred area of operation in which he achieved eminent success.
>
> He preferred to turn administrative duties over to me, so he could devote practically full time to research. I was also delegated to take charge of the testing personnel and operation of the testing floor. In preparing reports and publications, he did little longhand writing or stenographic dictating. He preferred to work with an assistant to whom he gave notes, which were converted to draft form and then reviewed. He was author of numerous papers and publications. He did not care to give speeches or take part in society meetings. He was a member of the American Society for Testing and Materials and the American Railway Association. For many years he was Secretary of ASTM Committee D–07 on Wood of which Dr. Herman von Schrenk was Chairman.

Robert Pilson Albert Johnson (1888–1962)

A native of Alexandria, Virginia, R.P.A. Johnson graduated from Virginia Polytechnic Institute and State University with a bachelor's degree in engineering and then earned a master's degree from the University of Wisconsin, Madison. In June of 1918, he joined the FPL as an engineer in the Division of Timber Mechanics under the direction of John Newlin. Specializing in lumber properties and grading, Johnson helped establish the first systems for lumber property assignment developed at FPL. During his career he was often honored for his contributions to the safe and efficient utilization of wood, and he ultimately became chief of the Division of Physics and Engineering at FPL. He was an active member of the American Institute of Timber Construction, Committee D7 of the American Society for Testing and Materials, the American Lumber Standards Committee, and the Committee on Bridge and Trestle Bridges of the American Railway Engineering Association. With the exception of 2 years on the War Production Board during World War II, Johnson spent his entire career at FPL and retired in 1958 with over 50 years of government service. The following is excerpt from an article in *Chips* by D.G. Colman:

> "Johnny," as he was affectionately called by all who knew him, was a personal friend of all who worked at the Forest Products Laboratory. Endowed with a warm, friendly, and sincere personality, probably no other person in the Forest Service has made more lasting and genuine friendships than Johnny. He was a firm supporter of "esprit de corps." Johnny did many big things—authored bulletins, delivered speeches, headed a Laboratory Division—but it was the little things that set him apart—a simple form for a legal will, a diagram of Government salaries compared with well-paid industry, a pocket lens for wood identification, a gentle Virginia drawl noticeable on nationwide radio hookups. These are but a few of the things that made Johnny a friend of mankind, a champion of wood, and a truly uncommon man.

William Emerson (1701–1782)

William Emerson, of Hurworth on Tees–County Durham, England, wrote several influential books in astronomy, physics, navigation, and mathematics. *The Principles of Mechanics* is described as "explaining and demonstrating the general laws of motion, the laws of gravity, motion of descending bodies, projectiles, mechanic powers, pendulums, centers of gravity, &c. strength and stress of timber, hydrostatics, and construction of machines." This book is characterized as "a work very necessary to be known by all gentlemen and others that desire to have an insight into the works of nature and art, and extremely useful to all sorts of artificers, particularly to architects, engineers, shipwrights millwrights watchmakers &c. or any that work in a mechanical way." Emerson described the organ of the middle 18th century and rightly concluded that "wood is likewise weaker when it is green and strongest when thoroughly dried." He designed sundials that show both the time and line of latitude. Emerson was offered the opportunity to join the Royal Society, but he turned down the offer in objection to paying dues for the right to place FRS after his name. He died on May 21, 1782, and is buried in the churchyard of All Saints Church in Hurworth.

It was a challenge to find pictures of the early pioneers who made important contributions to our understanding of the effect of moisture content on lumber properties. Some pictures, like the one of Walter Gilman Berg, required a long search and a measure of luck. The most unusual source was for the picture of William Emerson. We were told that a portrait of Emerson hangs in the Emerson Arms, a pub in Hurworth that overlooks the river, possibly in recognition of his fondness for ale and fishing. Thanks to the Internet, we managed to contact Hurworth IT Consultants, who kindly went to Emerson Arms and photographed Emerson's portrait.