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Janka Hardness Using Nonstandard Specimens

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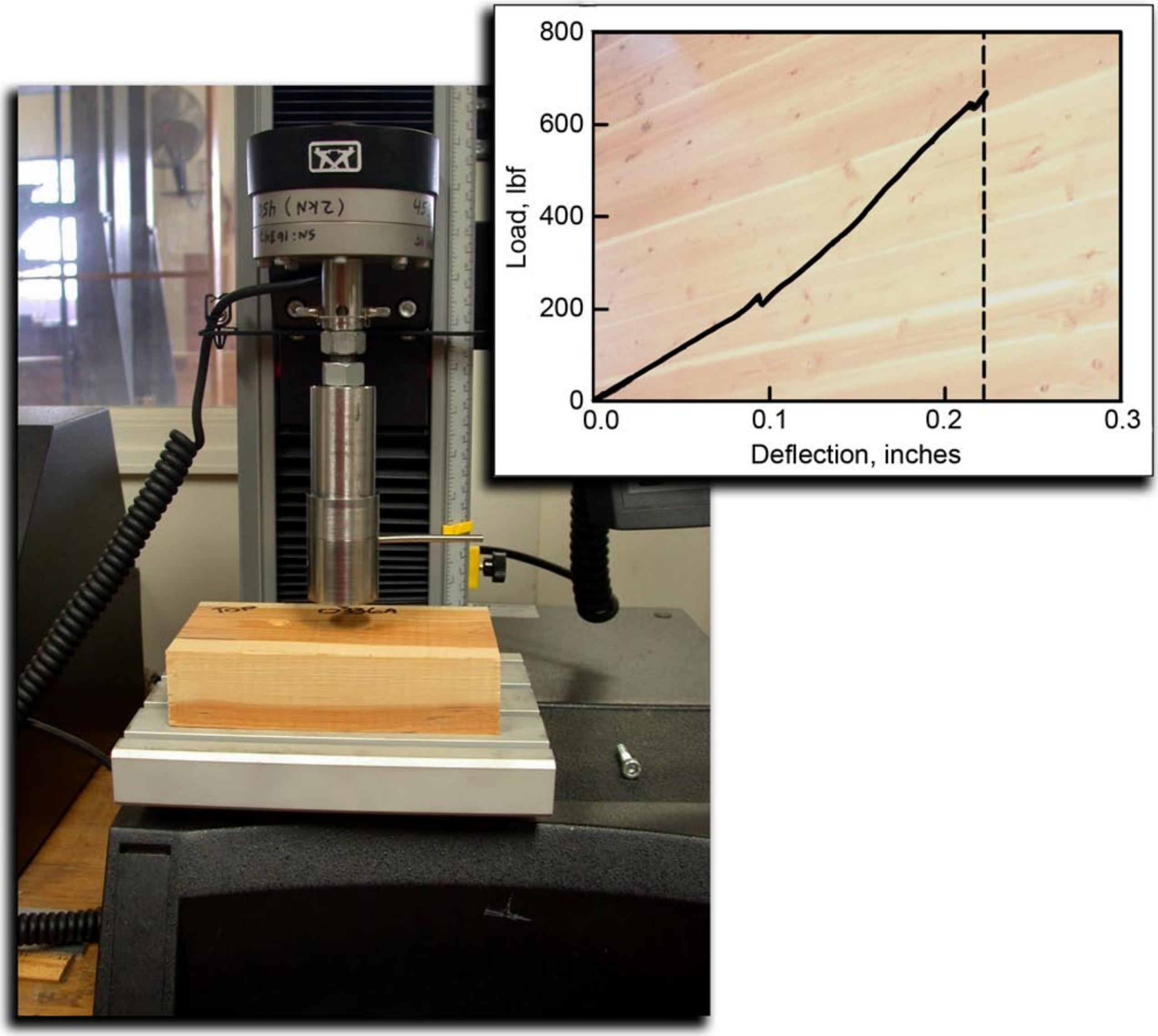

Abstract

Janka hardness determined on 1.5- by 3.5-in. specimens (2×4s) was found to be equivalent to that determined using the 2- by 2-in. specimen specified in ASTM D 143. Data are presented on the relationship between Janka hardness and the strength of clear wood. Analysis of historical data determined using standard specimens indicated no difference between side hardness values determined on the radial face as opposed to the tangential. Analysis of historical data also indicated that the relationship between hardness modulus (H_M) and Janka hardness (H) may be different for hardwood species than for softwood. Recommendations are given for ensuring that experimental procedures do not bias the results when testing non-standard specimens. The authors caution that if hardness (ASTM D 143) and hardness modulus (ASTM D 1037) are measured simultaneously for each ball penetration, the H_M/H ratio may be different than that given in D 1037 because the two standards specify different rates of penetration.

Keywords: Janka hardness, hardness modulus, Douglas-fir, 2×4

Metric conversion chart

Inch–pound unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter
pound (lb)	0.454	kilogram
pound–force (lbf)	0.27	Newton
temperature ºF	$(T_F - 32)/1.8$	temperature ºC

Contents

Acknowledgments

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Executive Summary

Background

The Janka ball hardness test has been specified for solid wood in ASTM standard D 143 since 1922. The standard calls for a specimen with a cross section of 2 by 2 in. Unlike the tests for some properties, this standard does not provide an alternative size of 1 by 1 in. The standard also requires tests on the radial and tangential faces of the specimen, with the average of the values obtained reported as the hardness of the specimen. The study presented here was prompted by our concerns about the results obtained when conducting Janka hardness tests on non-standard specimens. Hardness tests had been conducted on 1.5- by 3.5-in. specimens (2×4s) as part of a study of the properties of lumber cut from small-diameter Douglas-fir trees growing in dense stands.

Objectives

Our primary objective was to evaluate hardness values determined from tests on 1.5-in.-thick 2×4s compared to values that would have been obtained on standard 2-in.-thick specimens. The study included determining the effect of thickness on Janka hardness as well as a critical analysis of historical data and information on various factors that might affect Janka hardness. Our secondary objective was to provide additional information about the relationship between Janka hardness and the hardness modulus specified in ASTM D 1037.

Procedures

Hardness tests were conducted using indentations on the wide face of 2×4s at thickness values of 1, 1.5, and 3 in. The 1-in. data were obtained by planing the 1.5-in. 2×4 on the side opposite the indentations; the 3-in. results were obtained by either "stacking" the specimen to be tested on top of another 2×4 or by "gluing" the 2×4 to be tested to another 2×4. The test set-up allowed continuous recording of load as a function of penetration depth of the standard 0.444-in.-diameter steel ball into the specimen. Since hardness modulus is simply the relationship between the slope of the load and the penetration depth, it was possible to obtain both Janka hardness and hardness modulus from the same indentation.

Results

No difference in Janka hardness was found for thickness values of 1, 1.5, and 3 in. when the 3-in. depth was obtained by gluing together two 1.5-in.-thick specimens. Stacking two 1.5-in. specimens to obtain a 3-in. depth resulted in a lower hardness value than the value obtained with a glued specimen. An analysis of historical data for some selected hardwood and softwood species, including oak, indicated no real difference between standard hardness values with respect to the radial and tangential directions. We note that even very small "pin knots" in the projected path of the ball may effect hardness values and should thus be avoided. We also found that when using an automated routine to select load and deformation points off a continuous electronic record, it is important to ensure that the load reported for hardness corresponds very closely to a deformation of 0.222 in.

For all thickness values, the data indicated a ratio of hardness modulus to Janka hardness (H_M/H) of 4.9 as opposed to the value of 5.4 given in ASTM D 1037. This difference was attributed to two factors. First, the D 1037 ratio was originally developed by combining data for softwood and hardwood species. A reanalysis of the historical data indicated that whereas a ratio of 5.3 is appropriate for hardwood species, the ratio for softwood species should be 4.4. Second, the rate of loading specified for Janka hardness in both D 143 and D 1037 is 0.25 in/min, whereas D 1037 specifies a rate of 0.05 in/min for determining hardness modulus. These two properties can be determined by current specifications only by making two separate indentations for each property. In our tests, both Janka hardness and hardness modulus were measured on one indentation, using a rate of indentation of 0.25 in/min and resulted in an H_M/H ratio of about 4.9. We speculate that had we determined hardness modulus at a rate of loading five times slower, then the ratio of hardness to hardness modulus would have been lower and more in line with the expected result.

Conclusions

From our test results and a critical review of existing literature we conclude the following:

- Hardness values can be determined for 2×4s that are equivalent to those that would have been obtained by using the standard 2- by 2- by 6-in. specimen of ASTM D 143.
- If two pieces must be used to obtained a desired thickness, the pieces should be glued together.
- Continuous recording of load and deflection offers opportunities to better understand the results of Janka hardness tests on wood products, but care must be taken to ensure that the load reported is actually that at 0.222-in. deformation.
- There is no significant difference between hardness determined on the radial face as opposed to that determined on the tangential face, even for oak.
- Reanalysis of historical data indicates that the ratio of hardness modulus to Janka hardness may be different for hardwood and softwood species.
- When determining both Janka hardness (H) and hardness modulus (H_M) on a product, it may be important to realize that standard procedures for these tests require determining each property at different rates of loading. This will affect reported values for the H/H_M ratio.

Janka Hardness Using Nonstandard Specimens

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Introduction

As part of an evaluation of the properties of lumber cut from small-diameter Douglas-fir trees growing in dense stands (Green and others 2005), side hardness tests were conducted on nominal 2- by 4-in. lumber (hereafter called 2×4s) using the Janka ball hardness test procedure (ASTM D 143, ASTM 2005). This evaluation necessitated the use of a specimen having non-standard dimensions. In addition, the demise of our standard Janka jig (Fig. 1) provided an opportunity to measure ball penetration more precisely using a modern Instron (Instron Corp., Norwood, Massachusetts) testing machine (Fig. 2). The primary objective of this paper is to compare hardness values determined from tests on 1.5-in.-thick 2×4s to values that would have been obtained on a standard 2-in.-thick specimen. The analysis includes determining the effect of thickness on Janka hardness as well as critical analysis of historic data and information on various factors that might affect Janka hardness. A number of recommendations are given to ensure that experimental procedures do not bias the results with non-standard specimens. Because we recorded load and penetration continuously during our Janka hardness tests, we have also included some information about hardness modulus determined on our 2×4s and the historical relationship between hardness modulus and Janka hardness.

Background

Hardness is a term that has different meanings to different people. To the design engineer, it is resistance to plastic deformation or resistance to wear. To the tester of materials, it is resistance to indentation. To the machinist, it is resistance to cutting, and to the mineralogist, it is resistance to scratching. McClintock and Argon (1968) note that while these meanings may appear to differ greatly from each other, the equivalent plastic flow stress of the material is a common factor in each definition. They point out that indentation tests differ not only with regard to the shape of the indenter but also in the following ways:

- By using a fixed load and measuring the resulting diameter or width of the impression at the surface (Brinell hardness, Vickers hardness)

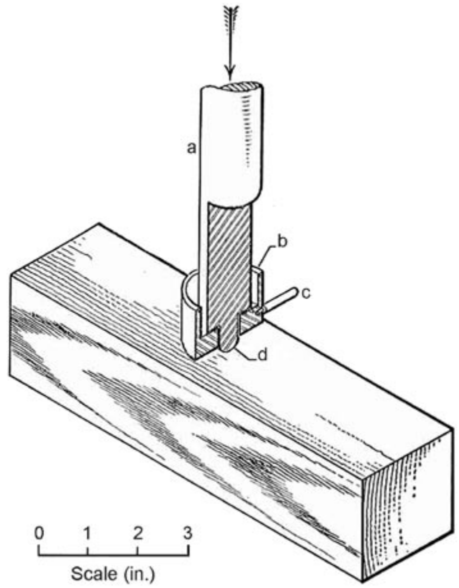

Figure 1—Historical equipment for ASTM D 143 test of Janka hardness: a, shaft of test jig; b, flexible collar; c, lever for “jiggling” collar; d, 0.444-in.-diameter ball drop.

- By using the contact area in computing the mean unit load on the indenter, or by using the projected area of the impression on the surface
- By using a fixed load and measuring the resulting depth of impression (Rockwell hardness)
- By using a variable load to produce a given depth of impression (Monotron hardness)
- By varying load on the indenter to produce impressions that range from macroscopic to microscopic

History of Standardization

The path to standardization of a hardness testing procedure for wood in the United States appears to have started in 1895 with the investigations of Filbert Roth, Special Agent in Charge of Timber Physics in the USDA Division of Forestry (predecessor of the Forest Service). In Bulletin 10, Roth and Fernow (1895) discuss wood hardness and show a rectangular piece of wood being imbedded directly into the

Figure 2—Modified Instron equipment for ASTM D 143 test of Janka hardness. Penetration depth of Douglas-fir 2×4 measured electronically.

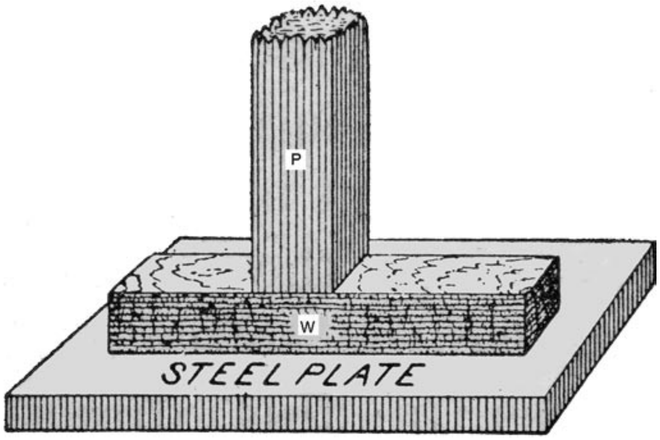

Figure 3—Early hardness test by Forest Service (Roth and Fernow 1895).

side of a wood specimen (Fig. 3). In 1905, W.K. Hatt, then in charge of the timber test program for the Forest Service (Green and Evans 2001), published “Instructions to Engineers of Timber Tests.” For hardness tests, this report stated that “an investigation will be made to determine appropriate methods of test. The method contemplated involves a measurement of the width of scratch made by a prescribed tool under a prescribed pressure.”

In 1906, Janka proposed a modified Brinell hardness test for wood (Kollmann and Côté 1968) based on the force required by static loading to embed a steel hemisphere with a diameter of 0.444 in., which corresponds to a circle with a projected area of $100\ \text{mm}^2$, completely into the wood. In 1910, W.K. Hatt sent a letter to McGarvy Cline, Director of the newly established USDA Forest Service, Forest Products Laboratory (FPL), summarizing the findings of Janka and suggesting that FPL should have a tool made and should perform some preliminary experiments (unpublished FPL correspondence). As will be further discussed in the next section, the Janka hardness test became a standardized procedure for clear wood tested at FPL and was eventually adopted by the American Society for Testing and Materials (ASTM). This procedure first appeared in ASTM records as D 143–22T[1] and became a standard procedure in 1927 with the formal adoption of D 143–27. Although originally expressed by Janka as a load divided by the projected area of contact, the D 143 hardness value has always been specified as the load (*H*) at a penetration of 0.222 in.

The standard specimen is a solid piece of wood with a cross section of 2 by 2 in. and length of 6 in. A distinction is made between hardness determined on the end and on the side of the piece. No distinction is made between hardness on the radial and tangential surfaces. The standard calls for two indentions to be made on the tangential face and two indentions on the radial face. The average value of the force (lbf) determined in the four indentations is reported as the side hardness. The test jig for the D 143 test procedure originally had a collar to which the ball was attached; the ball was penetrated into the specimen until the collar was tightened against the specimen (Fig. 1). In 1948, the use of an electronic circuit indicator was added as an option for determining depth of penetration. While many other types of tests have been proposed for determining the hardness of solid wood (for example, Kollman and Côté 1968, Weatherwax and others 1948,[2] and Doyle and Walker 1985), the Janka procedure has been the only method given in ASTM D 143.

Relationship of Janka Hardness to Other Properties

Strength Properties

In evaluating the results of hardness tests on 280 wood species, Janka found the following empirical relationship between hardness (*H*) and compression strength

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[1] The term 22T indicates a tentative standard published for comment in 1922.

[2] The report by Weatherwax and others (1948) provides references and some discussion of previous attempts to use other hardness test procedures with wood.

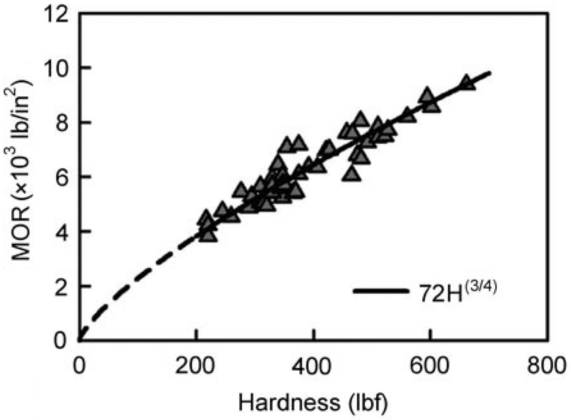

Figure 4—Side hardness and modulus of rupture (MOR) relationship for green conifers (Pettigrew and Newlin 1916).

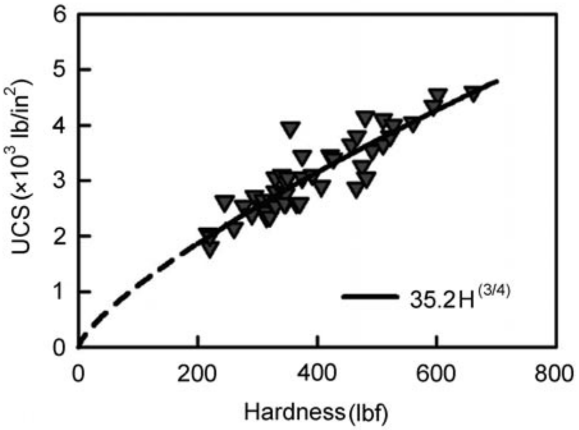

Figure 5—Side hardness and ultimate compressive stress (UCS) parallel to grain relationship for green conifers (Pettigrew and Newlin 1916).

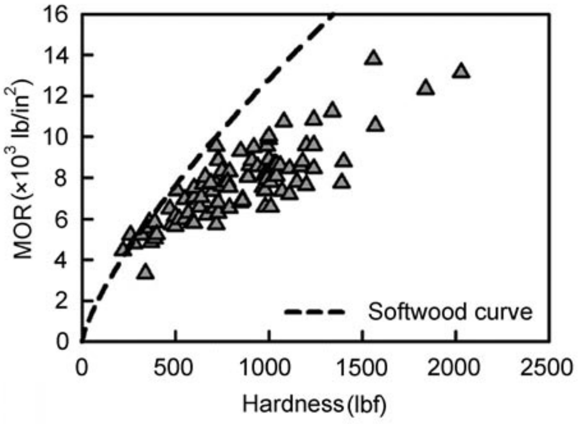

Figure 6—Side hardness and MOR relationship for green hardwoods (Pettigrew and Newlin 1916).

perpendicular to grain (C_{perp}) (Kollmann and Côté 1968):

$$H = 2C_{\text{perp}} - 500 \text{ (kp/cm}^2\text{)} \qquad (1)$$

Although suitable only for rough calculations, the relationship proves that the Janka hardness test is really a modified impression test influenced by effects such as friction, shearing, and cleavage.

Hardness as an indicator of wood strength was the focus of an unpublished FPL report in 1916 (Pettigrew and Newlin 1916). The authors noted that their data were based on 6 years of testing and represented 30 to 100 tests per tree for a minimum of five typical trees per species. In some cases, 60 or 70 trees were taken. (These data sets can no longer be identified and are not available.) The data summarized were average values per shipment for 48 shipments of conifers (about 37 species) and 91 shipments of hardwoods (about 85 species). For green conifers, a good relationship was found between Janka hardness and modulus of rupture (MOR) (Fig. 4):

$$\text{MOR} = 72H^{(3/4)} \qquad (2)$$

A good relationship was also found for green conifers between hardness and ultimate compressive stress (UCS) parallel to grain (Fig. 5):

$$\text{UCS} = 35.2H^{(3/4)} \qquad (3)$$

While MOR of hardwoods generally increases with increasing hardness (Fig. 6), this relationship was considered “very indefinite” and “an attempt to determine strength from hardness with any degree of accuracy would be useless” (Pettigrew and Newlin 1916).

In discussing the variability of the data from green conifers, Pettigrew and Newlin noted that over half the average MOR values for the 48 groups were within 4.5% of the predicted values and in no case were any groups further than 20% from the predicted values. For green compressive strength, values for over half the 91 groups were within 6% of the predicted values and none was more than 20% from the prediction. The authors noted that the relationships would be different for dry wood and that hardness would not be a good grading tool for lumber containing defects, because knots would influence MOR and UCS but not hardness.

Specific Gravity

Janka found that hardness is approximately proportional to the density of the wood (Kollmann and Côté 1968). Based on numerous measurements, Newlin and Wilson (1919) determined that the relationship between hardness and specific gravity (G) may be expressed as a power formula and derived the following equation:

$$H = AG^{n} \text{ (lb)} \qquad (4)$$

Newlin and Wilson gave separate coefficients, A and n, for green and dry wood, respectively, but did not separate hardwoods from softwoods. The current edition of the *Wood*

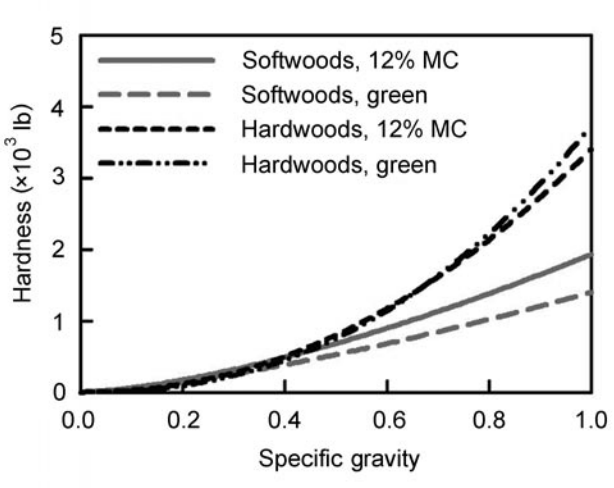

Figure 7—Janka hardness and specific gravity relationship (Table 1). MC is moisture content.

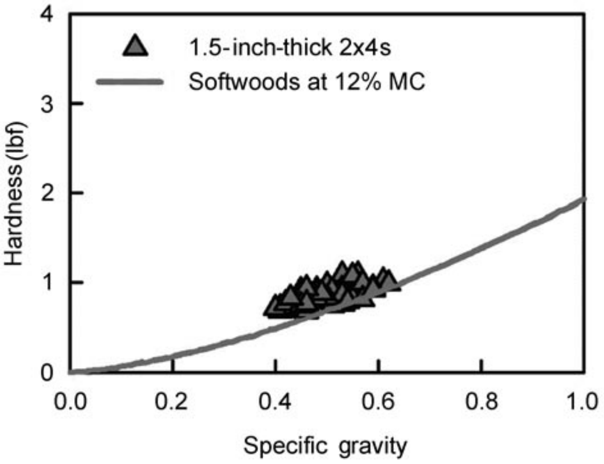

Figure 8—Hardness and specific gravity relationship for suppressed growth Douglas-fir 2×4s (Green and others 2005) compared to general relationship for dry softwoods (Table 1).

Handbook (Forest Products Laboratory 1999) provides separate relationships for Janka hardness and specific gravity for green and dry hardwoods and softwoods (Table 1). These general relationships are shown in Figure 7. Figure 8 compares the general relationship for softwoods at 12% moisture content to the hardness data collected for suppressed-growth Douglas-fir (Green and others 2005).

Load Placement and Specimen Thickness

When testing lumber, it may be necessary to determine the hardness of specimens less than 2 in. thick. It would appear obvious that as a specimen gets thinner, the stress field under the ball will eventually be affected by the hardness of the support surface (metal bed of testing machine in standard ASTM D 143 procedure). McClintock and Argon (1968) stated that when conducting the Brinell hardness test, the nearest edge of the specimen should not be closer than 2-1/2 impression diameters and the thickness should be greater than one impression diameter to obtain reliable readings. For the standard Janka ball, this recommendation indicates that the minimum specimen width would be 2.664 in. (2.5 × 0.444 + 0.444) and the minimum depth 0.666 in. (0.222 + 0.444).

Table 1. Relationship between Janka hardness (*H*) and specific gravity (*G*) for domestic species[a]

Species group	Moisture content	$H = AG^n$	
		A	n
Hardwood	Green	3,720	2.31
	12%	3,400	2.09
Softwood	Green	1,400	1.41
	12%	1,930	1.50

[a] Specific gravity is based on oven-dry weight and moisture content as indicated. Source: Forest Products Laboratory (1999).

Dohr (1946) made multiple determinations of Janka hardness using one piece of Sitka spruce with a cross section of 3 by 2 in. and length of 48 in. The specimen was conditioned to 12.6% moisture content and cut in such a way as to provide a straight-grained piece containing the same annual increment throughout its entire length. A series of 10 indentations was made on specimens ranging from 0.5 to 2 in. thick. The first series of 10 tests was made on the full 2-in. depth by distributing the hardness indentations throughout the length and width in such a manner as to obtain the best average for the piece. The specimen was then reduced in height by planing 1/4 in. from the bottom, and another series of tests was run. The results indicated no significant difference in average hardness with specimen thickness within the range tested (Table 2).

Dohr also compared the hardness of a specimen with a cross section of 1 by 1 in. with that of the standard 2- by 2-in. specimen. For Sitka spruce, no great difficulty was encountered using the smaller specimen. However, with southern pine and Douglas-fir, a high percentage of specimens split during the hardness test. Results from the smaller specimens that did not split were equivalent to those obtained with the standard specimen. Because of the high incidence of splitting, the smaller specimen was not recommended for testing hardness.

Growth Ring Orientation

The standard hardness test (ASTM D 143, ASTM 2005) requires two hardness impressions be taken in the radial direction and two in the tangential direction. These values are then averaged to obtain the hardness value for the specimen. Historically, only a limited number of individual radial and tangential hardness values have been published. We analyzed radial as opposed to tangential hardness for selected species in the FPL historical data base (Table 3). These data

Table 2. Effect of specimen thickness on Janka hardness of Sitka spruce[a]

Sample	Janka hardness (lbf) for various specimen heights (in.)							
	2.00	1.75	1.50	1.25	1.00	0.75	0.625	0.500
1	465	425	460	445	448	393	435	457
2	433	427	450	470	435	438	413	415
3	427	437	435	413	427	430	403	455
4	425	420	415	442	425	450	440	418
5	445	407	420	440	390	415	398	448
6	432	429	450	463	427	408	425	420
7	395	469	452	442	465	428	455	430
8	440	438	448	455	403	454	435	422
9	400	462	437	385	468	395	420	454
10	490	463	413	452	412	434	435	460
Average	435	438	438	441	430	425	426	438

[a] Source: Dohr (1946).

Table 3. Radial and tangential Janka side hardness of dry specimens[a]

		Janka side hardness (lbf)[b]										
		Radial				Tangential				Radial–Tangential		
Species	No. of samples	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	Min	Max
Douglas-fir[c]	1,258	639	143	320	1,200	671	161	305	1,268	–32	308	–454
Sitka spruce	290	499	94	310	770	508	111	327	838	–9	357	–236
Yellow-poplar	170	540	130	308	998	558	127	305	1,055	–17	182	–230
True hickory[d]	80	2,306	341	1,147	2,957	2,228	429	1,062	2,990	+79	1,243	–768
Red oak[e]	145	1,308	252	700	1,895	1,335	274	760	2,255	–29	580	–897

[a] Unpublished Forest Products Laboratory data.

[b] SD is standard deviation.

[c] Coast, interior north, and interior west.

[d] Mockernut, pignut, shagbark, and shellbark hickory.

[e] Northern red, black, scarlet, water, southern red, willow, pine, and California black oak.

were obtained using the standard specimen (ASTM D 143) after conditioning to 12% moisture content. The coefficient of variation of these observations averaged about 22%. As Table 3 indicates, the tangential values tended to be slightly higher than the radial values. For each specimen, we calculated the difference between hardness on the radial face and that on the tangential face. This information is summarized in the last three columns of Table 3. The mean difference was generally quite small (32 lbf for Douglas-fir), whereas the range of differences was quite large (radial–tangential values ranging 308 to –454 lbf for Douglas-fir). Thus, the differences in radial and tangential values are not significant, even for red oak. The primary reason to test both the radial and tangential faces appears to be to ensure a more representative value for each specimen. These findings are in agreement with the statement by Newlin and Johnson (1917) that "there is no consistent difference between radial and tangential hardness," and the values are averaged and tabulated as "side hardness."

Moisture Content

Below the fiber saturation point, side hardness increases with decreasing moisture content (Fig. 9). Weatherwax and others (1948) conducted tests with yellow birch and eastern white pine at four different moisture content levels. Although the results were not given in the paper, the authors stated that they were substantially equal to the adjustment recommendations for standard size specimens in ANC–18 (Table 4) (1951). For each 1% change in moisture content, the "average" change in side hardness for the 16 softwoods listed in Table 4 would be 2.75% and for the hardwoods 2.55%. The 1955 edition of the *Wood Handbook* (USDA 1955) lists a 2.5% change in side hardness for each 1% change in moisture content. This is an approximate method based on a compound-interest-type formula once recommended as an alternative to more accurate methods that were harder to calculate (Markwardt and Wilson 1935). This approximate method is no longer recommended. For moisture content values within the range of approximately 6% to 20%, change in hardness (*H*) with change in moisture

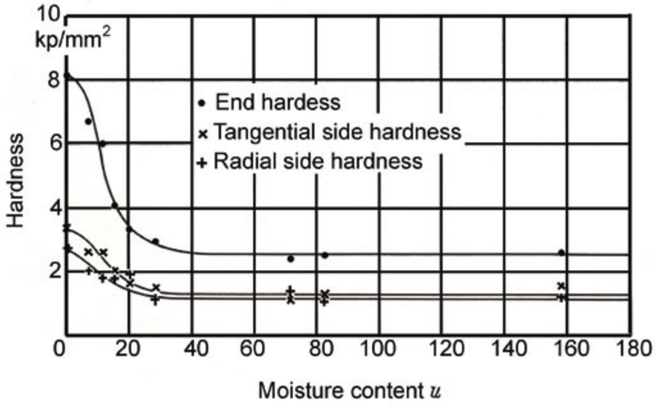

Figure 9—Effect of moisture content on Brinell hardness of pine (Kollmann and Côté 1968).

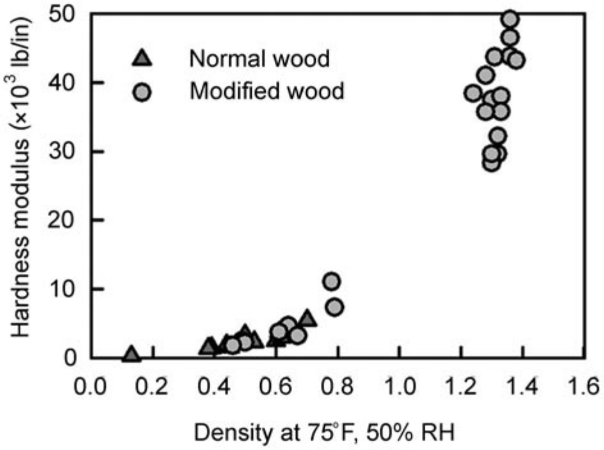

Figure 10—Hardness modulus (H_M) and density relationship for three species of normal wood and eight species of untreated modified wood (Weatherwax and others 1948).

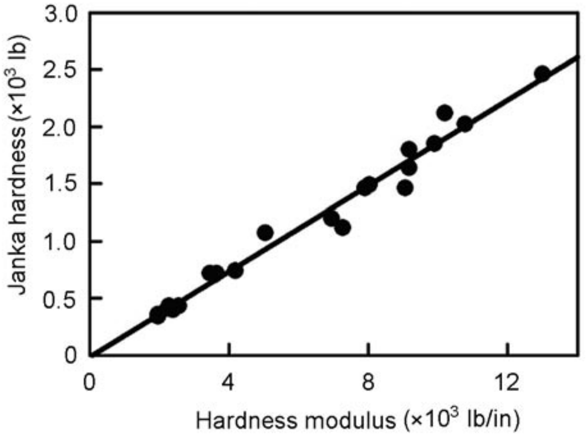

Figure 11—Janka hardness (H) and hardness modulus (H_M) relationship based on average results for selected hardwood and softwood species (Lewis 1968).

content (M) may be estimated from the following formula (Forest Products Laboratory 1999):

$$H = H_{12}(H_{12}/H_{\text{green}})^{[(12-M)/(M_p-12)]} \qquad (5)$$

where

H_{12} is hardness at 12% moisture content,
H_{green} hardness of green lumber,
M moisture content (%), and
M_p intersection moisture content (Table 5).

Hardness Modulus

As previously noted, the standard Janka ball may not be suitable for woods of very high specific gravity (splitting) or for thin laminates (insufficient depth). Weatherwax and others (1948) proposed an alternative approach using the standard Janka tool that would solve these problems. With the standard test, the applied force initially increases roughly linearly with depth of penetration. Weatherwax and others used the slope of this line to derive what they termed a hardness modulus. As noted by Doyle and Walker (1985), this is basically a Brinell hardness, the value of which will differ only if the linear portion of the plot does not pass exactly through the origin. In the 1948 studies, matched specimens were initially prepared from laminated veneer yellow-birch and eastern white pine of various thickness, from 0.09 to 1.006 in. After specimens were conditioned at 75ºF and 50% relative humidity, the hardness modulus was determined. Above a thickness of 0.25 in., hardness did not change with increasing thickness. To provide for an adequate safety factor, all subsequent samples were made at least 0.5 in. thick. The hardness modulus was then determined using 11 different species of untreated wood, both normal and compressed. The hardness modulus was shown to vary with density in a manner similar to that of the standard Janka hardness (Fig. 10). However, no direct relationship between Janka hardness and hardness modulus was provided.

Lewis (1968) investigated the relationship between hardness modulus and Janka hardness for a variety of wood and wood-based materials. Standard 2- by 2- by 6-in. specimens were manufactured using 11 species of solid wood, 9 particleboards, and 12 fiberboards. The specimens were equilibrated at 75ºF and 50% relative humidity. Hardness modulus was determined to a penetration depth of 0.1 in. and Janka hardness at the standard 0.222 in.. The load for the Janka hardness test was applied with a uniform rate of crosshead travel of 0.25 in/min, while that for hardness modulus was 0.05 in/min (as in the current standards, ASTM D 1037, ASTM 2005). From the reciprocal of the slope of the H vs H_M plot, it was determined that $H = H_M/5.4$ (Fig. 11). Doyle and Walker (1985) call this constant relationship a "fortuitous" finding that results from the compensation of increasing load by increasing projected contact area. The relationship between hardness modulus and Janka hardness

Table 4. Change in wood properties for 1% change in moisture content (ANC–18 1951)[a]

	Change in property (%)[b]							
	Static bending							
Species	Stress	MOR	MOE	WML[c]	C_{par}	C_{perp}	Shear	H (side)
Hardwood								
Ash, black	8.9	6.4	3.6	1.8	8.3	6.8	5.1	4.1
Ash, commercial white	4.1	3.5	1.4	0.4	4.7	4.8	2.9	2.4
Basswood, American	6.8	4.8	2.9	2.6	6.5	6.6	4.2	4.2
Beech, American	6.0	4.7	1.8	2.0	6.2	5.3	3.8	3.6
Birch, sweet	6.4	5.0	2.3	1.2	7.1	7.2	5.0	3.6
Birch, yellow	6.0	4.8	2.0	1.7	6.1	5.6	3.6	3.3
Cherry, black	6.6	3.6	1.1	1.0	6.0	5.5	3.5	3.1
Cottonwood	5.8	4.1	2.5	0.1	6.6	5.7	2.6	1.8
Elm, rock	4.7	3.8	2.1	–0.3	5.3	6.1	3.5	2.8
Hickory, true	4.9	4.8	2.8	–0.7	5.9	6.6	3.9	—
Khaya (African mahogany)	3.2	2.5	1.6	–0.6	3.2	3.0	0.4	3.1
Mahogany	2.6	1.3	0.8	–2.9	2.5	3.9	—	1.0
Maple, sugar	5.2	4.4	1.4	1.9	5.7	7.1	3.9	3.4
Oak, com. white and red	4.6	4.4	2.4	1.7	5.9	4.4	3.5	1.8
Sweetgum	6.7	4.7	2.2	1.5	6.1	5.4	3.5	2.4
Walnut, black	5.8	3.7	1.4	–2.6	4.8	6.3	1.0	1.0
Yellow-poplar	5.0	4.6	2.7	1.9	6.7	4.8	3.3	2.4
Softwood								
Baldcypress	4.6	4.0	1.6	1.8	4.9	5.1	1.7	2.3
Douglas-fir	4.5	3.7	1.8	1.9	5.5	5.0	1.7	2.9
Fir, noble	5.1	4.7	1.9	3.2	6.1	5.5	2.3	3.1
Hemlock, western	4.7	3.4	1.4	0.7	5.0	3.7	2.5	2.0
Incense cedar, California	3.4	2.1	1.8	–1.4	4.3	4.0	0.4	1.5
Pine, eastern white	5.6	4.8	2.0	2.1	5.7	5.6	2.2	2.2
Pine, red	8.0	5.7	2.2	4.7	7.5	7.2	3.9	4.5
Pine, sugar	4.4	3.9	2.1	0.1	5.4	4.4	3.7	1.9
Pine, western white	5.3	5.1	2.2	4.8	6.5	5.2	2.5	1.5
Redcedar, western	4.3	3.4	1.6	1.3	5.1	5.1	1.6	2.3
Spruce, red and Sitka	4.7	3.9	1.7	2.0	5.3	4.3	2.6	2.4
Spruce, white	5.8	4.8	1.9	2.1	6.5	5.7	3.7	3.3
White-cedar, northern	5.4	3.6	1.8	–1.5	5.9	2.3	2.8	3.0
White-cedar, Port Orford	5.7	5.2	1.6	1.7	6.2	6.7	2.2	2.8

[a] Corrections to strength properties should be made successively for each 1% change in moisture content until total change has been covered. Thus, for hardness, $H_M/H_{12} = (1 + A/100)^{(12-M)}$, where H_M is hardness at some desired moisture content M, H_{12} is hardness at 12% moisture content (USDA 1955), and A is the factor given in Table 4.

[b] Stress is fiber stress at proportional load; MOR, modulus of rupture; MOE, modulus of elasticity; WML, work to maximum load; C_{par} and C_{perp}, compressive strength parallel and perpendicular to grain, respectively (C_{par} is maximum crushing strength); shear, shearing strength parallel to grain; H, hardness.

[c] Negative values indicate decrease in WML for decrease in moisture content.

is standardized for wood-based composites in ASTM D 1037 (ASTM 2005).

Beginning with the 1987 edition of the *Wood Handbook*, the relationship between Janka hardness (H) and specific gravity was determined by whether the species were hardwoods or softwoods. We decided to determine if the H_M–H relationship also varies by species group, using Lewis's data for solid wood (Tables 6 and 7). A plot of the individual values indicated that two tangential observations and three radial observations for southern pine appeared to be outliers (Fig. 12). Lewis did not comment on these outliers, but since he plotted mean values of H_M and H for the combined data they would have had little effect on the predicted H_M–H relationship. As can be seen from Table 8, these outliers have a profound effect on the H_M–H relationship when the individual observations for softwoods are plotted. With the inclusion of the southern pine outliers, the H_M–H relationship is different for radial as opposed to tangential hardness, but without the outliers the relationship is the same for radial and tangential hardness (Fig. 13).

Table 5. Intersection moisture content (M_p) of selected species[a]

Species[b]	M_p (%)
White ash	24
Yellow birch	27
American chestnut	24
Douglas-fir	24
Western hemlock	28
Western larch	28
Loblolly pine	21
Longleaf pine	21
Red pine	24
Redwood	21
Red spruce	27
Sitka spruce	27
Tamarack	24

[a] Source: Forest Products Laboratory (1999).

[b] For other species, use $M_p = 25$.

Table 6. Hardness and hardness modulus for tangential and radial faces of selected hardwood species and grades[a]

			Hardness of selected lumber grades									
			Hardness modulus (lbf/in.)					Janka hardness (lbf)				
Species	MC (%)	Load[b]	No. 1	No. 2	No. 3	No. 4	Avg.	No. 1	No. 2	No. 3	No. 4	Avg.
White ash	9.3	T	9,150	9,210	9,330	8,970	9,160	1,545	1,620	1,710	1,680	1,640
		R	8,050	7,690	7,870	8,000	7,900	1,510	1,440	1,420	1,450	1,460
Hickory	8.1	T	12,800	13,300	13,000	12,800	13,000	2,370	2,450	2,480	2,550	2,460
		R	11,200	9,700	10,700	9,400	10,200	2,220	1,950	2,220	2,080	2,120
Yellow-poplar	9.7	T	2,220	2,400	2,460	2,430	2,380	405	405	405	385	400
		R	1,890	2,050	2,030	1,820	1,950	385	370	360	335	360
Red oak	9.2	T	5,080	5,380	4,490	5,170	5,030	1,100	1,020	1,080	1,090	1,070
		R	8,820	8,700	8,960	9,760	9,060	1,460	1,455	1,450	1,480	1,460
Sugar maple	8.0	T	9,400	9,090	8,980	9,150	9,160	1,795	1,720	1,750	1,930	1,800
		R	9,340	7,650	7,870	7,220	8,020	1,580	1,440	1,520	1,410	1,490
Ohia	8.2	T	10,870	10,410	11,170	10,630	10,770	2,020	2,050	2,000	2,000	2,020
		R	9,530	9,530	10,200	10,310	9,890	1,900	1,820	1,780	1,900	1,850

[a] Source: Lewis (1968). MC is moisture content.

[b] T is tangential, R radial.

Table 7. Hardness and hardness modulus for tangential and radial faces of selected softwood species and grades[a]

			Hardness of selected lumber grades									
			Hardness modulus (lbf/in.)					Janka hardness (lbf)				
Species	MC (%)	Load	No. 1	No. 2	No. 3	No. 4	Avg.	No. 1	No. 2	No. 3	No.4	Avg.
Redwood	7.2	T	2,380	2,310	2,170	2,120	2,240	385	405	415	425	410
		R	2,440	2,340	2,230	2,080	2,270	420	440	445	405	430
White pine	7.3	T	2,110	3,000	2,670	2,450	2,560	430	445	430	420	430
		R	2,030	1,950	1,900	1,970	1,960	335	355	335	345	340
Douglas-fir	10.4	T	4,270	3,980	4,460	4,000	4,180	670	750	830	730	740
		R	3,400	3,760	3,680	3,720	3,640	700	700	720	740	720
Southern pine	9.9	T	5,610	8,760	5,080	8,330	6,940	1,145	1,115	1,330	1,215	1,200
		R	5,330	7,690	8,330	7,690	7,260	1,140	1,110	1,080	1,170	1,120
Ponderosa pine	8.0	T	3,800	3,680	3,410	3,380	3,570	700	685	685	710	700
		R	3,450	3,120	3,720	3,500	3,450	755	715	700	710	720

[a] Source: Lewis (1968).

Table 8. Relationship between Janka hardness (*H*) and hardness modulus (H_M) calculated using data of Lewis (1968)

Species grouping	Direction	Data[a]	$H = A + BH_M$			Factor[b]
			A	B	R^2	
Hardwoods	Tangential	All	26.438	0.187	0.98	5.3
	Radial	All	−18.973	0.190	0.93	5.3
Softwoods	Tangential	All	159.118	0.138	0.75	7.2
	Radial	All	180.987	0.131	0.81	7.6
	Tangential	Reduced	−139.493	0.232	0.86	4.3
	Radial	Reduced	−93.113	0.228	0.97	4.4
Hardwoods	Both	All	2.269	0.187	0.96	5.3
Softwoods	Both	Reduced	−105.983	0.227	0.90	4.4
All	Both	Reduced	10.361	0.187	0.97	5.3

[a] Reduced data refer to the dropping of two tangential observations and three radial observations for southern pine.

[b] Factor = $1/B = H_M/H$.

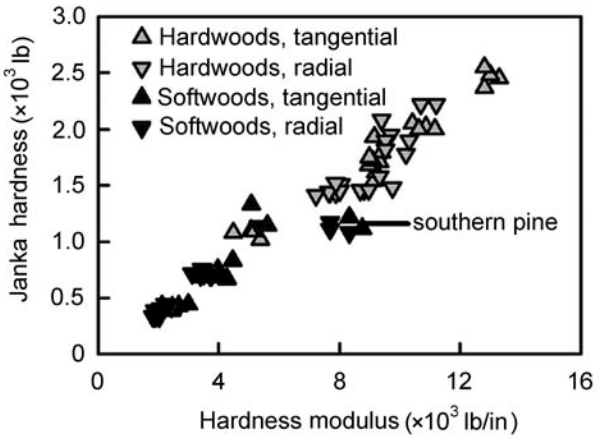

Figure 12—Janka hardness and hardness modulus relationship based on individual radial and tangential values for selected hardwoods and softwoods (Tables 6 and 7) (Lewis 1968).

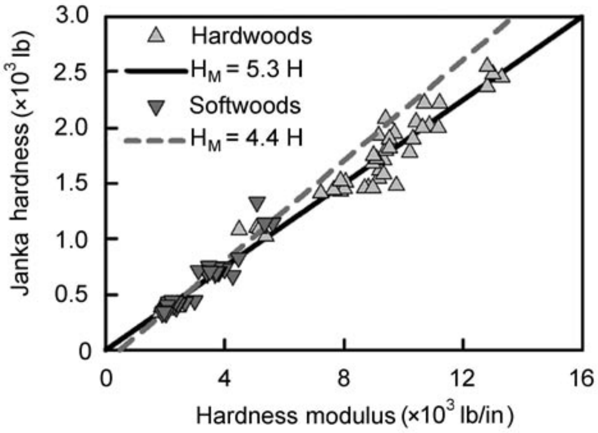

Figure 13—Janka hardness and hardness modulus relationship. Data from Lewis (1968), excluding some southern pine results.

For hardwoods there is also no difference in the H_M–H relationship based on the direction of penetration. When the radial and tangential data are combined, the analysis for hardwoods and softwoods combined indicates that H_M is 5.3 times the value of H, a result that is very close to the value of 5.4 obtained by Lewis using mean values for all data. If the hardwood and softwood data are examined separately, the ratio for hardwoods is 5.3, the same as that given by Lewis. Excluding the southern pine outliers, the combined radial and tangential data for softwoods indicate that H_M is only 4.4 times the value of H. The reason for the difference between our results and those of Lewis can be seen in Figure 13. When the hardwood and softwood data is combined, the large range of H_M for hardwoods (almost twice that for softwood data) overwhelms the softwood trend and the combined data has a H_M/H factor of 5.3. Based on this analysis, we conclude that a separate factor should be used for softwoods and hardwoods when H_M is to be used to estimate H.

Having reviewed the background for hardness testing of solid-sawn and composite wood products in ASTM standards using the Janka ball procedure, we will now discuss observations resulting from our investigation of the Janka ball test for solid-sawn dimension lumber.

Procedures

Material

As noted earlier, this study originated as a follow-up to hardness tests conducted on 120 Douglas-fir 2×4s cut from small-diameter, suppressed-growth trees (Green and others 2005). The specimens were a random subset of 902 2×4s tested in bending and were cut from the undamaged ends of the subsample. The original hardness specimens had a cross section of 1.5 by 3.5 in. and were 6 in. long. The hardness indentations were taken on the wide (3.5-in.) face, and therefore the specimens had a thickness of 1.5 in. For most of the 2×4s, the pith was located somewhere in the cross section. Although indentations were not made directly at the pith when it was located near the wide surface of the sample, it was not possible to ensure either a purely radial or purely tangential orientation for the test surface. Two ball impressions were made on one side of each specimen. Prior to testing, the specimens were stored in a humidity chamber at 68ºF and 68% relative humidity for several months.

Testing

Testing followed the procedures of ASTM D 143 (ASTM 2005). Because our old test jig was worn out, we manufactured a new one that still had a 0.444-in.-diameter ball but that would connect to an Instron testing machine (Fig. 2).[3] Load was measured using a calibrated load cell having a maximum range of 2,000 lbf. Deflection was measured as machine crosshead movement, with its origin corresponding to the position of the load head at a small (less than 1 lbf) load. The crosshead movement could be accurately recorded to the nearest 0.0001 in. The sampling rate for collection of the electronic load–deflection data was 1/s for the 1.5-in.-thick samples, but it was increased to 10/s for the other thickness levels to provide better resolution. In addition, a threshold was set to automatically record the “maximum load” at an indentation of 0.222 in. (see Discussion).

Following the initial determination of Janka hardness on the 120 2×4s, 61 pieces were selected for additional testing. First, hardness tests were conducted on a 3-in.-thick specimen. This thickness was obtained by placing untested pieces of 1.5- by 3.5- by 6-in.-long 2×4s under the original tested specimens. These specimens will be referred to as “3-in. stacked” specimens. For these specimens, a second pair of indentations was obtained on the same face as used for the 1.5-in. thickness. No impressions were taken within two ball diameters of a previous indentation or within two ball diameters of the specimen edges. Following these tests, the original specimens were planed on the untested face to a thickness of 1 in. and the specimens tested again on the original face.

After an analysis of the data for all three thickness values, we decided to test a 3-in. thickness using two 2×4s glued together (termed “3-in. glued”). Approximately sixty 6-in.-long pieces of lumber from the original study remained in conditioned storage. Although not the same pieces as tested at 1, 1.5, and 3 in. (stacked), these pieces were from the same sample and thus would be expected to have approximately the same hardness as that of the original specimens. The pieces were glued together with a polyvinyl acetate adhesive and pressure applied per the manufacturer’s recommendations. Following gluing, twenty-nine 3-in.-thick specimens were available for testing. Two indentations were made on one face of each specimen.

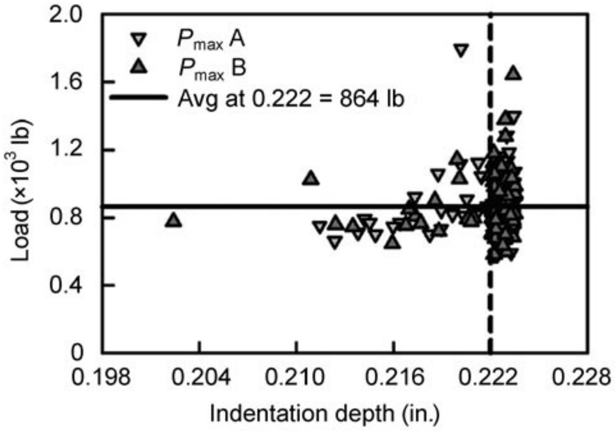

Figure 14—Initial load–indentation plot for Douglas-fir 2×4s prior to reanalysis. P_{max} indicates maximum load for two impressions (*A*, *B*) on each specimen.

For all thickness values, the slope of the load–deflection curve was calculated by taking a linear regression of the points between 20% and 40% of the load at 0.222 in. of penetration. These data were used to determine the hardness modulus. These percentages correspond fairly consistently to a penetration range of 0.06 to 0.10 in. This matches the recommendations of Lewis (1968), which were subsequently incorporated into ASTM D 1037 (ASTM 2005).

Results and Discussion

Janka Hardness

Validity of Individual Values

Our Inston testing machine can be set to shut off at a prescribed amount of crosshead movement and to output both the measured penetration and the maximum load (P_{max}) recorded during the test. Figure 14 shows a plot of such data for each impression (P_{max} *A* and P_{max} *B*) taken on each 2×4. Note that a few specimens were “outliers,” with penetration below 0.220 in. The recorded P_{max} value was sometimes higher and at other times lower than the average of the P_{max} loads at 0.222 in. of penetration. These outliers would probably not have been identified with the older procedure of “jiggling” the handle on the collar until it became tight (thus indicating penetration to 0.222 in.). With the electronic system it is sometimes possible, for example, to identify that a higher P_{max} value occurred at a penetration lower than 0.222 in. because the ball had penetrated a latewood band but the P_{max} value had dropped slightly by the time 0.222 in. of penetration was reached. Thus, the newer procedure may offer additional insights into the data, but it presents challenges to ensuring that the standard is followed precisely. To ensure that we were using the load required by

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[3] Note that the new hardness jig still contains a handle that could be used to “jiggle” the collar, but this option was not used in this series of tests.

Table 9. Effect of specimen thickness on Janka hardness of suppressed-growth Douglas-fir 2×4s at 12% moisture content

Thickness (in.)	Specimen type	Sample size[a]	Janka hardness (lbf)						Equality[c]
			Mean	COV[b]	5th	25th	50th	75th	
1.0	Solid	61	867	12.1	690	801	875	917	A
1.5	Solid	61	858[d]	11.0	718	794	864	913	A
3.0	Glued	29	902	17.2	645	792	900	941	A
3.0	Stacked	61	743	13.3	606	670	730	800	B

[a] Values reported are the average of *A* and *B* impressions.

[b] Coefficient of variation (COV) = 100 × (standard deviation/mean).

[c] Mean thickness values with same letter are not significantly different by Tukey standardized range test at 0.05 confidence level.

[d] For all 120 specimens tested at thickness of 1.5 in., mean hardness = 864 lbf (Green and others 2005).

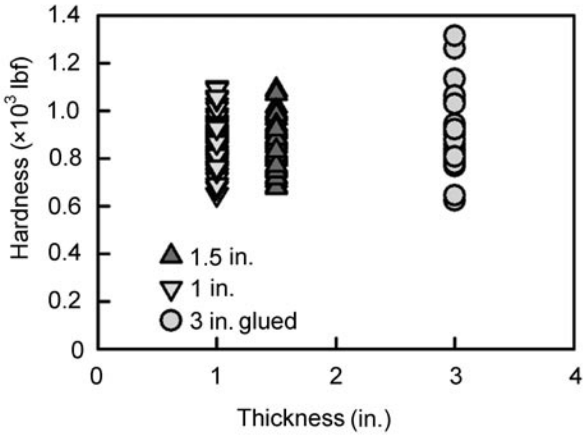

Figure 15—Effect of thickness on hardness of Douglas-fir.

ASTM D 143, we analyzed the load–penetration data and recorded the load precisely at 0.222 in. of penetration. These loads are the basis for the hardness values discussed in this paper.

Plots of the *A* versus *B* impression for all the pieces also helped us identify problems with an individual observation. We found that a larger than expected difference between the *A* and *B* impressions could occasionally be traced to a slight imperfection, usually a pin knot, somewhere beneath the impression location. The electronic capture of the load–deflection curve was found to be more sensitive than expected to such imperfections. Imperfections in a lumber sample are sometimes impossible to avoid. However, it is important that the cross section be inspected carefully and that it contain no imperfections anywhere throughout the thickness within about two ball diameters (say 3/4 to 1 in.) of the location chosen for an impression.

Analysis of Results

Table 9 summarizes the Janka hardness values for each thickness group. The average moisture content of all specimens was 12.2%. As would be expected from the literature, there was no significant difference between the results for the 1- and 1.5-in. thickness. There was also no difference between these results and the results for a 3-in.-thick specimen if the two pieces were glued together. A plot of hardness as a function of thickness yielded an R^2 value of 0.076, which also confirms the lack of a significant trend between hardness and thickness (Fig. 15). However, the hardness of the 3-in. specimen obtained by simply stacking two 1.5-in.-thick specimens together was about 13% lower than the mean for the 1.5-in.-thick specimen and about 18% lower than that for the 3-in. glued specimens. We speculate that perhaps the two stacked specimens did not produce perfectly flat contact surfaces. Lack of good contact between specimens could have allowed a slight springiness, which could act to slightly reduce the hardness value. Gluing is the method specified in ASTM D 1037 for obtaining the hardness of thin veneers. Our results support these recommendations.

Janka Hardness and Hardness Modulus

Hardness modulus values were also obtained for each Douglas-fir specimen using the load–penetration data (Table 10). As with Janka hardness, only the results for the 3-in. stacked specimens were significantly different. The results for the stacked specimens were about 16% lower than the results for the 1.5-in. specimens.

A ratio of hardness modulus (H_M) to Janka hardness (H) was calculated for each piece to determine a factor that might be used to multiply by H_M to estimate H (Table 11). For this calculation, the ratio was calculated separately for the *A* and *B* impressions and the overall mean values obtained. Thus, the sample sizes in Table 11 are twice those listed in Tables 9 and 10. These values were then plotted and the slopes of the curves determined for the 1- 1.5-, and 3-in. glued specimens. As previously shown, H and H_M values for the 3-in. stacked specimens were not the same as those for the other groups, so a regression relationship was not determined for the stacked specimens. As can be seen from Figure 16 and is quantified in Table 11, the relationships are the same for all three groups. Thus, we conclude that the relationship between H and H_M is not a function of specimen thickness within the range of thickness values studied.

Table 10. Effect of specimen thickness on hardness modulus of suppressed-growth Douglas-fir 2×4s at 12% moisture content

Thickness	Specimen	Sample	Hardness modulus (lbf/in.)						
(in.)	type	size[a]	Mean	COV	5th	25th	50th	75th	Equality[b]
1.0	Solid	61	4,203	14.5	3,383	3,741	4,119	4,628	A
1.5	Solid	61	4,382	18.8	3,357	3,444	4,304	4,757	A
3.0	Glued	29	4,289	21.0	3,172	3,622	4,278	4,573	A
3.0	Stacked	61	3,588	16.3	2,648	3,216	3,574	3,980	B

[a] Values reported are average of *A* and *B* impressions.

[b] Mean thickness values with same letter are not significantly different by Tukey standardized range test at 0.05 confidence level.

Table 11. Ratio of hardness modulus (H_M) to Janka hardness (H) for suppressed-growth Douglas-fir 2×4s at 12% moisture content

Thickness		Sample	Factor = H_M/H			$H = A + BH_M$			
(in.)	Condition	size	Mean	Min	Max	A	B	R^2	Equality[a]
1.0	Solid	122	4.76	3.63	5.98	156.2	0.1728	0.82	A
1.5	Solid	122	5.07	3.55	7.33	243.4	0.1409	0.67	A
3.0	Glued	58	4.76	3.52	6.75	261.5	0.1494	0.74	A
3.0	Stacked	122	4.83	2.82	6.16	(—[b])	—	—	—

[a] Equations relating H and H_M with same letter are not significantly different at 0.05 confidence level.

[b] Because there were significant differences between 3-in.-thick glued values and other thickness values for both H and H_M, it is not appropriate to evaluate the regression relationship.

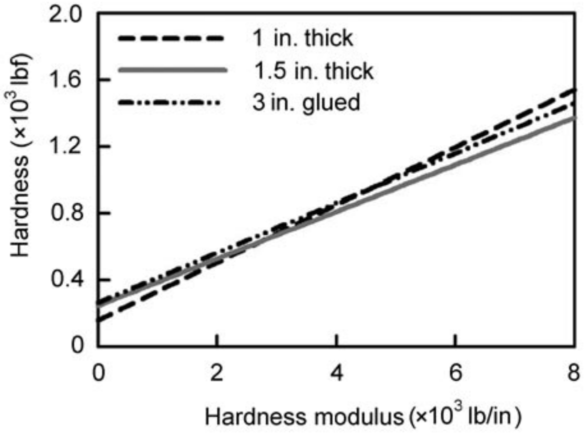

Figure 16—Hardness modulus and Janka hardness relationship for different thicknesses of Douglas-fir.

The mean value of the ratio for the 1.5-in.-thick pieces was 5.07, and the overall average for the 1-, 1.5, and 3-in. glued specimens was 4.86 (Table 11). These ratios are higher than the average ratio of 4.4 that we expected from the reanalysis of the softwood data of Lewis (1968) given in Table 8. Two differences between our test procedure and that used by Lewis are notable. First, the softwood specimens tested by Lewis had about 8.6% moisture content, whereas moisture content of our specimens was about 12%. However, if we were to adjust our data to 8.6% moisture content using Equation (5) for both H_M and H, the ratio would not change and thus moisture content would not help explain the difference between our expected results and the observed results. The second notable difference is that because we took both H and H_M from the same impression series, the rate of loading for the calculation of both H and H_M was 0.25 in/min. Lewis obtained H using a loading rate of 0.25 in/min, but obtained H_M with a second impression on the same material using a loading rate of 0.05 in/min (as now specified in ASTM D 1037). We were unable to find specific information on the effect of loading rate on H or H_M, but it is well known that properties perpendicular to the grain are more sensitive to rate of loading effects than are properties parallel to the grain. In a statistical analysis of the effect of five factors (species, direction of loading, rate of loading, moisture content, and tree) on the properties of wood in compression perpendicular to the grain, Bodig (1966) found rate of loading to be the most important single factor. Thus, it appears likely that our H_M–H ratio would be lower had we tested H_M at a rate five times slower, as did Lewis.

Conclusions

From the results of our study we conclude the following:

- Janka hardness values for Douglas-fir determined on 1.5-in.-thick 2×4s are equivalent to those determined on a standard 2-in.-thick specimen.
- Continuous electronic recording of load and deflection data offers opportunities for more precise determination

of the factors influencing Janka hardness. However, care should be taken to ensure that the load is recorded precisely at 0.222 in. of penetration.

- Analysis of historical data for selected species indicates no significant difference between Janka hardness values taken on radial and tangential faces, even for oak.
- Reanalysis of the 1968 data of Lewis indicates that the traditionally assumed H/H_M ratio of 5.4 may be different for solid-sawn hardwoods (5.3) than for solid-sawn softwoods (4.4).
- When determining Janka hardness (H) and hardness modulus (H_M) for a given material, it is important to realize that standardized procedures call for determining H using a crosshead speed of 0.25 in/min.
  (ASTM D 143) and H_M at 0.05 in/min. Our results indicate that the ratio between H and H_M might be significantly different if the same rate of crosshead motion were used for both indices.

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