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Engineering Properties of Douglas-fir Lumber Reclaimed from Deconstructed Buildings

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Abstract

A vast wood resource exists in our Nation's wood-framed building infrastructure. As the buildings in this infrastructure age and are remodeled or removed for redevelopment, the wood framing residing in these buildings has the potential to be recovered for reuse. However, little technical information exists on the residual engineering properties of reclaimed dimensional lumber.

Our study was undertaken to quantify the engineering strength and stiffness of dimensional Douglas-fir 2-by lumber recovered from building dismantlement or deconstruction. These data can serve as a basis for establishing formal recognition of this resource in current grading rules and engineering design standards.

Keywords: lumber, salvaged, reclaimed, deconstruction, engineering properties

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Conversion table

To convert from	To	Multiply by
inch (in.)	millimeter (mm)	25.4
foot (ft)	meter (m)	0.3048
lb/in^2	pascal (Pa)	6.8948×10^3
acre	ha	0.4047
English unit	**Formula**	**SI unit**
temperature (°F)	$[T_F - 32]/1.8$	temperature (°C)

Billion and trillion are used as defined in the U.S. System as 10^9 and 10^{12}, respectively.

Contents

Executive Summary

Background

A vast wood resource exists in our Nation's wood-framed building infrastructure. When buildings or other wood structures reach the end of their useful life, the structural lumber and timber can be salvaged and reused in new construction and remodeling. Little technical information exists on the residual engineering properties of this lumber. To what extent the damage found in reclaimed lumber (resulting from original construction, a lifetime of use, and the dismantlement process) affects lumber strength has not been quantified.

Objective

The primary objective of this paper is to quantify the engineering properties (most importantly bending strength and stiffness) of full-size 2-by lumber reclaimed from buildings slated for demolition. This paper also documents lumber clear-wood strength as well as the effect of various forms of damage on lumber bending strength, including edge-nail holes, face-nail holes, and splits.

Procedures

Lumber was salvaged from buildings to be demolished at four different locations. The collected lumber was graded on-site by a lumber grading supervisor. Two grades (Select Structural and No. 2) of three sizes (2 by 6; 2 by 8; and 2 by 10) were returned to the Forest Products Laboratory, Madison, Wisconsin, for laboratory testing. Several thousand pieces of lumber were graded to yield the 1,078 full-size pieces tested. This lumber was tested in bending to determine modulus of elasticity (MOE) and modulus of rupture (MOR). Lumber characteristics (knots, slope-of-grain, checks, etc.) and damage (nail holes, bolt holes, splitting, etc.) were quantified for each piece. Small clear bending specimens were also cut (where possible) from the failed lumber. These were tested according to ASTM standards to determine clear-wood strength.

Results and Conclusions

The following was found from the testing and analysis of reclaimed Douglas-fir lumber:

The mean bending strength of full-size Douglas-fir lumber was found to be about 25% lower than in-grade test data of the same species. Mean stiffness was about 10% higher than in-grade test data. Existing size-effect equations are applicable for reclaimed lumber. No geographical location effect was found for the four locations tested. Nail holes reduced MOR when they were closely spaced or if they had created further splitting, primarily when located at the high-stress tension edge. In testing this reclaimed lumber, shear failures were found to be relatively common though the bending strength of this lumber was higher than lumber failing at knots. Compared with lumber that has damage as the grade-determining defect, the frequency of lumber failures involving damage were less common, suggesting that grading may be too conservative regarding damage. In addition, lumber failing at points of damage exhibited higher bending strength than lumber failing at knots.

Results of mean bending strength of clear wood and mean specific gravity were essentially the same as that from historical data. Mean MOE was about 10% greater than that of historical data. Differences in MOR between geographical groups of lumber from different locations can be explained by differences in specific gravity.

Recommendations

The following recommendations are made about regrading and reuse of salvaged lumber:

- Reclaimed lumber should be regraded before reuse. Grading rules, and possibly design guidelines, should formally recognize this material and provide guidance regarding appropriate reuse.
- Any requirements for reuse should recognize the impracticality of identifying the exact species of each piece of 2-by lumber salvaged and accommodate some degree of species mixing.
- In design, regular edge-nail holes should be placed in the compression zone, or away from the highest tension zone.

Engineering Properties of Douglas-fir Lumber Reclaimed from Deconstructed Buildings

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Background

During the last century, millions of residential homes, commercial and industrial buildings, bridges, and other structures have been built from sawn lumber and timber. As these structures age, lumber will become available for reuse (through remodeling or deconstruction). Since the turn of the 20th century, over 3 trillion board feet of lumber has been produced in the United States (Falk and others 2003). Much of this lumber still resides in our aging building infrastructure. Wood buildings are regularly coming out of service because of functional or conditional obsolescence or both, and demolition is typically the disposal method of choice. The U.S. Environmental Protection Agency estimates that the equivalent of 250,000 single-family homes are demolished each year in the United States (EPA 1998). By recovering the structural lumber alone in these buildings, over 1 billion board feet of usable lumber (after estimated recovery losses) could be reused rather than landfilled (Falk 2002). This volume represents about 3% of our current annual softwood harvest (Howard 2001).

Maximizing reclaimed lumber has positive environmental effects. First, more fully utilizing reclaimed lumber will reduce the volume of waste destined for landfills. Second, the reuse of building products reduces the volume of new building products that need to be produced and the associated production of greenhouse gases. Finally, the reuse of lumber will help conserve our natural resources and ease harvesting pressure on the existing forest resource.

Lumber Grading

To assure satisfactory performance in construction applications, structural lumber of a specific species is graded into quality classes at the saw mill. Grading agency rules contain grading criteria that are used to visually (or mechanically) sort lumber into quality classes. These criteria include specific limits on the size and location of strength-reducing characteristics such as knots, splits, checks, and slope-of-grain. To determine appropriate end-uses for the various quality grades, ASTM D 1990 engineering testing is performed on full-sized lumber (ASTM 2002). These test results are used to establish engineering design properties (e.g., strength, stiffness) and assure that the lumber will perform satisfactorily when used in a particular application. The various lumber grades are typically indicated by a lumber grade stamp that allows each piece to be individually sold and allows lumber's widespread acceptance by engineers, architects, and building officials at the building site.

Because existing grade criteria have been developed for lumber fresh from the saw mill, the current rules do not specifically address some characteristics commonly found in reclaimed lumber, such as multiple nail holes and damage from long-term use or damage from the dismantlement process. The damage found in reclaimed lumber takes many forms and is a result of original construction, a lifetime of use, and the dismantlement process. To what extent these characteristics affect lumber strength has not been quantified, and limitations in the existing grading rules can result in reclaimed lumber being unnecessarily downgraded or disallowed for reuse.

Establishing a grade stamp specific to reclaimed lumber will allow each piece to be individually sold and accepted at building sites. Currently, lumber and timber are regularly salvaged from industrial buildings for use in timber-frame construction. For the most part, the reclaimed structural lumber and timber used in timber-frame construction is regraded and individual engineering designs are approved by a licensed engineer. Because 2-by lumber is more ubiquitous, it would be more practical to develop a grade stamp specific to reclaimed 2-by lumber so that each regraded piece can be individually sold.

Previous Research

Very little research has been performed on reclaimed dimensional lumber. Limited testing by Falk and others (1999c) suggested that reclaimed Douglas-fir lumber may have different engineering properties than today's sawmill-produced lumber. Because the lumber tested in the 1999 study was a mixture of species and grades, group sample sizes were too small to make definite conclusions at other percentiles. Falk and others (1999b) also examined the effect of damage on the grade yield of lumber reclaimed from military barracks and found that accounting for deconstruction damage reduced lumber quality by about one grade.

Non-destructive methods have been used to evaluate the elastic modulus of in-place floor joists (Lanius and others 1981), and the clear-wood strengths of 85-year-old roof trusses were examined by Fridley and others (1996). Small clear specimens cut from truss members showed no difference in compression parallel-to-grain and flexural properties compared with historical data. However, these studies did not include destructive testing of full-size lumber to determine strength and stiffness.

Other studies have examined the mechanical properties of larger dimension timbers. Testing 8-in. by 8-in. columns of 55-year-old timber revealed compressive strength and modulus of elasticity (MOE) to be greater than current National Design Specification for Wood-derived values (NDS 2001, Falk and others 2000). Another study determined that large heart checks reduced mean bending strength of 6-in. by 8-in. reclaimed Douglas-fir timbers by about 15% but had no effect on stiffness (Green and others 2001). Rammer (1999) also found that splits and checks have a considerable effect on the residual shear strength of reclaimed timbers. The data reported in this paper originated, in part, from Maul (2004).

Selection of Lumber for Testing

This research effort involved a sampling plan designed to test reclaimed Douglas-fir lumber of various size, quality, geographical locations, and prior uses. Current methods to derive design properties for visual grades of commercially produced solid sawn dimension lumber are outlined in ASTM standard D 1990 (2000). This standard suggests testing two grades of lumber (separated by no more than one grade) and three sizes (with no more than 4 in. nominal depth between sizes). Ideally, 360 specimens should be tested for each size-grade cell for statistical confidence.

The three sizes of lumber tested in this study were 2 by 6, 2 by 8, and 2 by 10. These sizes were thought to be the most likely sizes for reuse given their common usage in single-family home construction. Though a 2 by 4 size is very common, we thought that it was less likely that this size would be reused in large-scale structural applications because of the high incidence of nail damage to these relatively small profile members. At the larger end, 2 by 12s could have been tested; however, we thought that this size is not as common in home construction as the three sizes chosen, and therefore chose not to test it.

ASTM D 1990 also suggests testing two grades of lumber, separated by one grade, so we chose Select Structural (SS) and No. 2. The lumber was collected from four building deconstruction sites and had been used as floor joists, roof rafters, wall members, stringers, and collar ties. Several thousand pieces of full-size lumber salvaged from deconstruction were graded to yield the 1,078 pieces of No. 2 and SS tested. Lumber that had been painted was not included in this study.

Locations

The collection of lumber for this project was more problematic than for most lumber studies. Because building deconstruction is not yet a universal practice throughout the United States, it was difficult finding a large quanity of lumber in a particular geographic area during the research project. For this reason, we acquired lumber from deconstruction projects that were active during the period of the project, despite these projects not being as geographically diverse as we originally hoped.

Lumber could have been obtained from the deconstruction of single-family homes or from the wide array of reuse centers and small deconstruction projects across the country (Falk and Guy 2005). However, the small number of pieces available from any one such source would severely limit the statistical conclusions to be drawn from the resulting test data. For example, the deconstruction of a single residential home may only yield 50 pieces of full-size lumber available for grading. After grading, only a few pieces might end up in each cell. Because decommissioned military bases offered relatively large buildings that were the same age, type, and purpose, they were ideal targets for this study. The buildings were typically larger than a single residential home and yielded a greater number of lumber pieces for a given size–grade cell.

The lumber tested in this study was collected from deconstructed buildings at four sites: (1) barracks and warehouse, Fort Ord, Marina, California; (2) warehouse, Oakland Naval Supply Center, Oakland, California; (3) military housing, University of Washington Campus, Seattle; (4) warehouses, Twin Cities Army Ammunition Plant (TCAAP), New Brighton, Minnesota. All buildings were wood framed and had been built in the early 1940s in preparation for World War II.

Fort Ord

A pilot deconstruction project of a two-story barrack (Fig. 1) and a light-framed warehouse at the Fort Ord Army base in Marina, California, yielded 2 by 8 floor joists and stringers and 2 by 6 roof rafters. Loading was likely very light, consisting of the dead load of floor and roof systems and coverings as well as intermittent light live load from

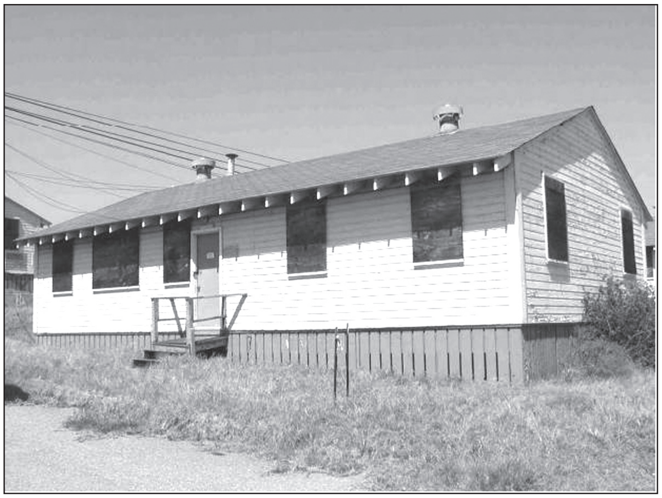

Figure 1—Single story Army barrack, Fort Ord, Marina, California.

foot traffic; snow in the region is extremely rare. At Fort Ord, we tested 370 pieces of lumber:

Size	Grade	Quantity
2 by 6	No. 2	98
	SS	12
2 by 8	No. 2	220
	SS	40

The lumber quantified is a subset of the lumber that served as the basis for the 1999 lumber grading study by Falk and others (1999b).

Oakland Naval Supply Center

Two groups of lumber were retrieved from buildings at the Oakland Naval Supply Center in California. These buildings, approximately 65 years old, served as warehouse and light manufacturing space at this World War II-constructed facility. Wall studs (2 by 6) as well as roof joists (2 by 10) were removed by deconstruction crews (Fig. 2). Roof loading was most likely limited to the dead loads of roofing material and miscellaneous hanging mechanical and electrical equipment, as snow is almost nonexistent in this area. The exterior wall studs bore the dead load of the wood-framed roof, wind loads, and possibly earthquake loading from intermittent quakes. However, no damage or overstress was apparent in the structure from which the lumber was salvaged. We tested 313 pieces of lumber from the Oakland Naval Supply Center:

Size	Grade	Quantity
2 by 6	No. 2	16
	SS	47
2 by 10	No. 2	53
	SS	197

Figure 2—2 by 6 wall studs from the Naval Supply Center warehouse, Oakland, California.

Twin Cities Army Ammunitions Plant

The Twin Cities Army Ammunitions Plant (TCAAP) is located in New Brighton, Minnesota, on a 2,383-acre site and originally had 255 buildings. Construction began in 1941 and ammunitions production for World War II began in early 1942. Roof joists were collected for our study from one of the industrial wood-framed buildings (Fig. 3). The roofs from which the joists were collected were flat and subjected to heavy Minnesota snow loads, as well as dead loads consisting of the roofing materials and miscellaneous mechanical, electrical, and plumbing equipment that hung beneath. Only 2 by 10s were available from the TCAAP. The 170 pieces of 2 by 10 lumber tested includes previously tested lumber from Falk and others (1999c):

Size	Grade	Quantity
2 by 10	No. 2	53
	SS	117
	Total	170

University of Washington

The final group of lumber tested in this study came from the University of Washington in Seattle. Old university housing units, once used for the U.S. Army, were dismantled and the lumber collected (Fig. 4). All members were either roof rafters or floor joists. Loading was likely very light, consisting

Figure 3—Twin Cities Army Ammunition Plant (TCAAP) warehouse, New Brighton, Minnesota, before deconstruction.

Figure 4—University of Washington housing units, Seattle.

Figure 5—Crew grading lumber from University of Washington housing units, Seattle.

of the dead load of floor and roof systems and coverings as well as intermittent light live load. We tested 225 pieces of lumber at the University of Washington:

Size	Grade	Quantity
2 by 6	No. 2	20
	SS	36
2 by 8	No. 2	43
	SS	2

A total of 1,078 pieces of full size lumber were tested at all locations:

Size	Grade	Quantity
2 by 6	No. 2	134
	SS	95
2 by 8	No. 2	387
	SS	42
2 by 10	No. 2	106
	SS	314
Total	No. 2	627
	SS	451
Grand total		1,078

Grading Tested Lumber

After removal from the buildings, all lumber was evaluated on site, where possible, by a WCLIB grading supervisor and followed Standard No. 17 Grading Rules for West Coast Lumber (WCLIB 2000) (Fig. 5). The lumber was graded as Structural Joists and Planks. Basically, all lumber salvaged from the buildings was screened first for length. Ideally, pieces of the following lengths were selected for testing: 2 by 6, 10 ft; 2 by 8, 12 ft; and 2 by 10, 14 ft. This provided the length necessary for end trimming (considered in grading) and resulted in a 17:1 span-to-depth ratio as required by testing standards (ASTM D 198 (2000)).

Some characteristics found in reclaimed lumber are not specifically addressed in the published grading rules. For example, the allowable number of nail holes in a particular piece is not specified. Though the grading rules do limit the size of a “hole” (from any cause) in the same category as Unsound or Loose Knots, there is no guidance on the equivalency of multiple nail holes and a particular size knot hole. Importantly, no information exists to suggest that a particular number of nails (concentrated or distributed) have the same effect on lumber failure as an unsound knot.

In addition to the grading rule descriptions, the lumber grader was asked to evaluate damage from deconstruction. For example, splits that obviously occurred from dismantlement (indicated by the fresh break) were noted, as was end damage from prying members from the building. The grader used his best judgment about the effect of nail holes on

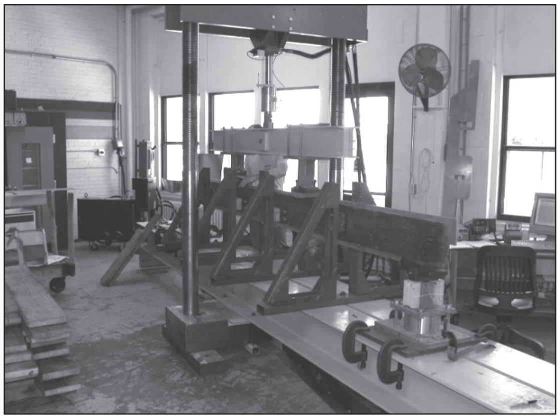

Figure 6—Reclaimed 2 by 10 lumber is tested on a Riehle Universal Twin Screw test device at the Forest Products Laboratory, Madison, Wisconsin.

Table 1—Species of No. 2 and SS-grade lumber tested

	Location				Totals	
Species	Fort Ord	UW[a]	TCAAP[b]	Oakland	*n*	(%)
Douglas-fir	318	226	123	313	980	91
Larch			11		11	<1
Hemlock	12		15		27	2
Sugar pine	4				4	<1
White pine	3				3	<1
Western yellow pine	12		14		26	2
Sitka spruce	15				15	1
Western cedar	3				3	<1
White fir	1		2		3	<1
Eastern yellow pine			6		6	<1
Total	376	226	171	313	1,078	100

[a] University of Washington, Seattle.
[b] Twin Cities Army Ammunition Plant, New Brighton, Minnesota.

grade. Also, mechanical gouging was equated to established wane requirements. An evaluation of the effects of this damage on grade yield can be found in Falk and others (1999b). Damage found in the end 12 in. of each board was ignored.

Species Identification

One major difference in lumber obtained directly from a sawmill and lumber from salvage is the assurance of species uniformity. Lumber from a sawmill typically originates from a single species stream as identified by the bark, needles, and geographic origin of the tree. On the other hand, salvaged lumber comes from a building that may contain a mixture of species that could be a result of the original building material supply chain or remodeling and repair (or both). Unless a grade stamp exists (which in our experience with this World War II-era lumber is often infrequent), species uniformity cannot be guaranteed. Also, visual identification to confirm species presented a potential problem with reclaimed lumber because some of the lumber was dirty or discolored. Though 1,078 pieces of lumber were collected and graded as Douglas-fir, species identification by the USDA Forest Products Laboratory's Wood Identification Unit determined that only 980 actually belonged to this species. Table 1 indicates the other species present. Note that species variation only occurred in lumber salvaged from Fort Ord and Minnesota. Lumber from the University of Washington and Oakland was exclusively Douglas-fir. In total, over 90% of the lumber salvaged was Douglas-fir.

Moisture Content

Field measurement of lumber moisture content (MC) using a moisture meter was made periodically. The MC of several hundred pieces was measured and ranged from 8% to 14%. This is a very reasonable finding, as the outdoor equilibrium moisture content in the West and Midwest is about 12%.

Testing Methodologies

Full Size Bending

Pretest Procedure

Upon completion of visual grading and specimen numbering on site, the lumber was transported to the Forest Products Laboratory and stored in a covered location. Most lumber had all nails removed before shipment from the deconstruction site; however, many required trimming to a consistent length. All lumber was stickered and stacked in a humidity-controlled room for several weeks prior to testing. This room was maintained at 75°F and 65% relative humidity (12% equilibrium MC).

Board identification numbers were logged and dimensions of each piece (length, width, and depth at center of span) were measured. Nail holes were counted over a designated length to calculate average spacing. We made extensive lab notes and included information on damage and natural defects, including location in the test span, size, and type. The Appendix shows a data collection sheet used for each specimen. Static modulus of elasticity (MOE), modulus of rupture (MOR), specific gravity (SG), and MC were determined for each full-size test specimen.

Bending Tests

Static bending tests followed ASTM D 198 (2000); however, the speed of the test was modified so failure occurred in approximately 1 min, rather than the 10 min specified in the standard.

Each board was tested in a Riehle Universal Twin Screw test device shown in Figure 6. Using a 10,000-lb. hydraulic actuator, each board was tested on edge in third-point bending

Table 2—Failure code descriptions

Failure code	Failure type	Comments
1	Tension (wood)	Type
2	Tension (knot)	Type, size, damage involved?
3	Tension (damage)	Type of damage
4	Tension (slope of grain)	Slope, damage involved?
5	Compression	Type, damage involved?
6	Horizontal shear	Type, damage involved?
7	Invalid test	Specify
8	Other	Specify

until failure. A constant displacement of 2 in. per min resulted in failures initiating in approximately 1 min. Electronic instrumentation included a 10-kip capacity Honeywell Sensotec load cell (Honeywell Sensing and Control, Columbus, OH), and a linear variable differential transducer (LVDT). The LVDT was attached to a yoke suspended between nails driven in at the neutral axis above the two reaction points. The LVDT stem was then attached to a nail driven in at the center of the board at the center of the test span. This setup measured the deflection of the center of the piece relative to the end supports. Where possible, boards were tested at a span-to-depth ratio of 17:1. Some boards were not long enough to achieve this ratio, and were tested at slightly lower ratios (15:1). Corrections to the data were made to account for these lower ratios.

During testing of the Oakland 2 by 10 lumber, a load-cell error was discovered that affected 49 pieces of lumber. As indicated in appendix C of Maul (2004), a review of the load-cell calibration curves and a statistical analysis of the data allowed the development of an error-correction factor so that the data could be salvaged.

Post-Test Procedure

We established a code for describing the various failure types (Table 2) and after each test, we assessed the type of failure and recorded a determination whether or not damage was involved in the failure. Failure types were grouped according to the mechanics of the failure (tension, compression, and horizontal end shear). The board was then sawn into manageable lengths and a section of the board saved for cutting a small clear specimen for future testing (Fig. 7). A moisture block was cut from the failed board shortly after testing to calculate MC and SG per ASTM D 4442 (2007) and ASTM D 2395 (2000), respectively. After determining MC, this moisture block was given to the FPL Wood Identification Unit for determination of species. A photograph of failure was also taken of every board. A 3-ft-long section of the board centered at the failure was cut for future strength–ratio grading.

Figure 7—Tested lumber marked for cutting small clear specimens.

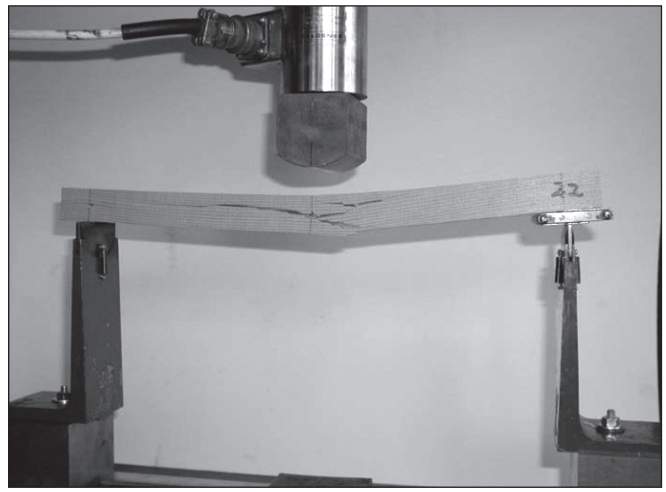

Figure 8—Small clear specimens are tested in center-point bending.

Small Clear Bending

Pretest Procedure

Preparation of small clear specimens followed the secondary method of static bending in ASTM D 143 (2007). After cutting to the specified 1-in. by 1-in. by 16-in. size, the specimens were placed in a humidity-controlled room for several weeks to achieve approximately equilibrium MC (75°F, 65% RH). The specimens were carefully examined to assure all pieces were clear of defects. Specimens were rejected that contained defects such as pin knots, slope of grain (SOG) 1:20 and steeper, and nail holes. This adherence to the ASTM standard ensured an unbiased comparison to historical data.

Static Bending Tests

All small clear specimens were tested in center-point bending at a span of 14 in. per ASTM D 143 (2000) (Fig. 8).

Table 3—Reclaimed and historical small clear data for Douglas-fir

Property	Reclaimed			Historical	Difference
	No.	Mean	COV[a]	mean[b, c]	mean (%)[d]
MOR ($\times 10^3$ lb/in^2)	622	13.59	16.3	13.7[e]	0.7
MOE ($\times 10^6$ lb/in^2)	622	2.06	18.4	1.86	10.8
Specific gravity (12% MC)	582	0.48	11.1	0.49	2.0
Moisture content (%)	586	11.4	8.9	12.0	5.0

[a] Coefficient of variation is standard deviation/mean.
[b] Average of Coast, Interior West, and Interior North regions.
[c] Percentage difference is (historical average – reclaimed average) / historical average.
[d] As reported in the *Wood Handbook* (FPL 1999).
[e] Historical MOR adjusted from 2 in. depth to 1 in. (see Eq. (1)).

This standard specifies a displacement rate of 0.05 in. per min, and using this rate resulted in failures in approximately 10 min. To make the testing timeline more reasonable, this rate was modified to 0.1 in. per min to achieve failure in approximately 5 min. All data were gathered with a similar electronic data acquisition system that was used with the full-size bending tests. A LVDT attached to an aluminum yoke was used to measure the deflection at the center relative to the supports. Load was measured with a 1-kip capacity Sensotec load cell.

Post-Test Procedure

After the specimen had failed, notes were taken including the time until failure and type of failure. A block was then cut from the specimen for use in calculating SG and MC. Failed pieces were saved for future studies.

Test Results

Testing results are presented for both small clear specimen testing as well as full-size lumber tests. To analyze the data, a commercial statistical software package, SAS (v 8.2, SAS Institute Inc., Cary, NC) was used under the guidance of FPL statistical staff. All regression analyses were performed using SigmaPlot (v 7.101) (Systat Software, Inc., San Jose, CA).

Small Clear Results

A common assumption among wood researchers is that the properties of wood do not change appreciably with time, unless acted on by destructive or other actions that degrade (e.g., overloading, decay). To verify this assumption, the small clear data were analyzed and compared to available historical data on small clear wood properties. As stated earlier, these small clear specimens were cut from the full-size members.

Small Clear Specimens

Property Comparison to Historical Data

A total of 827 small clear specimens were tested; 26 were discarded from this analysis because they were species other than Douglas-fir or larch, and 52 were discarded because of an inconsistency discovered in the test setup. The properties for small clear samples (127 total pairs) taken from the upper and lower section of the lumber were averaged to maintain a sampling representative of the full-size lumber sample (Maul 2004). This resulted in a total of 622 pieces of data included in this analysis (smaller for some properties because of data sampling problems). Table 3 summarizes the calculated properties and shows a comparison to historical values. For both the reclaimed and historical data, specimens were conditioned to 12% MC; however, the historical data set was generated from testing 2- by 2-in. specimens. Obviously, this size specimen was impossible to produce from the reclaimed 2-by lumber tested in this study, so a 1- by 1-in. specimen was used as allowed under ASTM D 245 (2000). Both data sets were tested with center-point bending at a span-to-depth ratio of 14:1, so a size adjustment was applied to the historical small clear MORs to allow comparison to the 1- by 1-in. reclaimed small clear data per ASTM D 245 (Eq. (1)). This factor was found to be 1.08 for this case with d_1 = 2 in. and d_2 = 1 in.

$$MOR_2 = MOR_1\left(\frac{d_1}{d_2}\right)^{1/9} \qquad (1)$$

where

MOR_1 is modulus of rupture at d_1,
MOR_2 modulus of rupture at d_2,
d_1 member depth 1, and
d_2 member depth 2

As observed in Table 3, the MORs for the reclaimed small-clear tests were only slightly lower than historical averages. The historical data were generated by taking the average of the means for Coast, Interior West, Interior South, and Interior North Douglas-fir from the *Wood Handbook* (FPL 1999) because we don't know the specific origin of the reclaimed lumber. The specific gravities were nearly the same with a mean difference of about 2%, which indicates similarity of the reclaimed resource to the historical data.

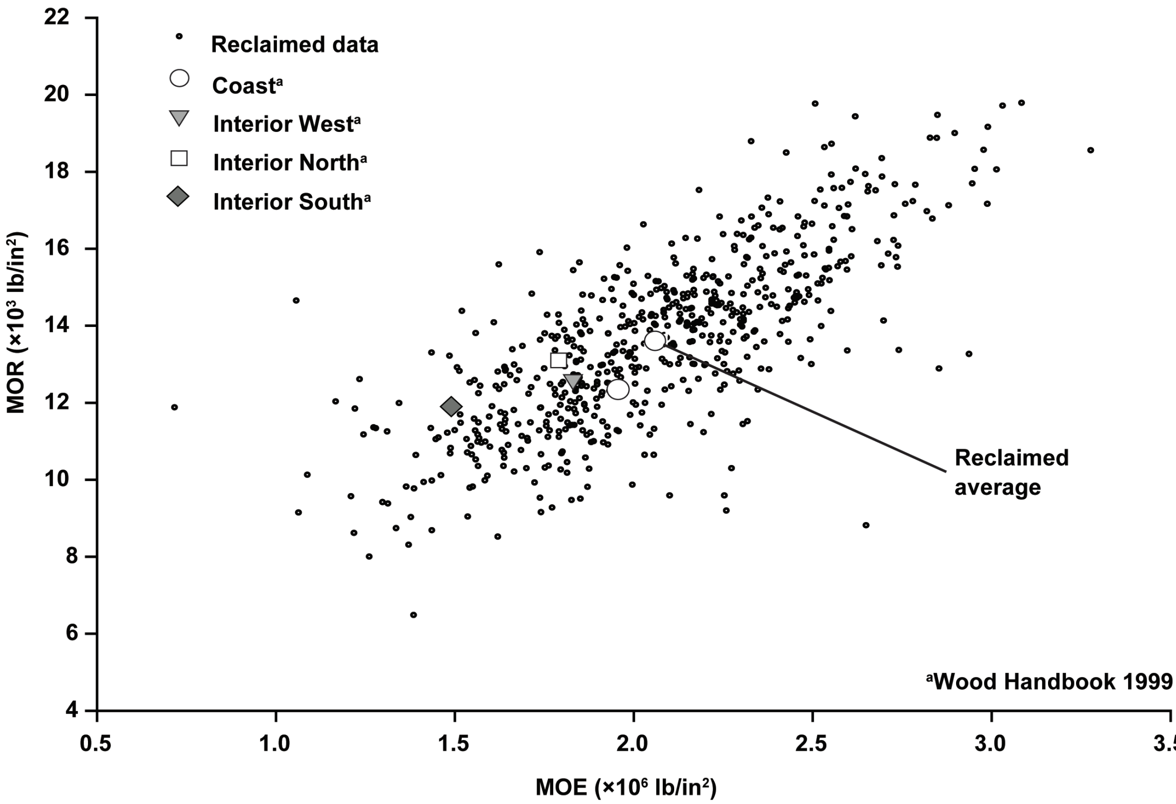

Figure 9—Comparison of reclaimed small clear data to historical averages of modulus of elasticity (MOE) and modulus of rupture (MOR).

Only the MOEs differ and reclaimed small-clear stiffness is greater than historical averages by approximately 11%. This is also depicted in Figure 9 as a plot of MOE compared with MOR. Note that only summary statistics were available for the historical data, so a comparison was only possible at the means.

Property Relationships

Specific gravity is known to be a predictor of bending MOE, which is a general predictor of MOR. Research has shown that within a species, these properties can be modeled using a linear function (FPL 1999). These relationships are illustrated for the reclaimed small clear data in Figures 10 to 12. Linear regression lines for SG compared with MOR, SG compared with MOE, and MOE compared with MOR are also shown. Specific gravity data shown are at 12% MC. As indicated in Figures 10 and 11, SG is a better predictor of MOR than of MOE. However, MOE is a better predictor of MOR (Fig. 12) than is SG (Fig. 10).

Location Comparison

The clear wood properties of the lumber salvaged from different locations were also evaluated. Statistical analyses were performed in which simultaneous comparisons of the groups were made for three properties: MOR, MOE, and SG. All species were included in this comparison. Both sizes of lumber collected from Oakland (2 by 6 and 2 by 10) exhibited higher MOR values than the 2 by 6 Fort Ord and 2 by 8 Washington groups, based on 95% or higher confidence (Table 4). Similar trends are shown for both MOE (Table 5) and SG (Table 6). The SG for the 2 by 6 Fort Ord lumber is lower than every other group except the 2 by 8 lumber from Washington (Table 6).

The correlation between these three properties can be illustrated by ranking the means, for each size-location, for each property. Based on this observation, it is reasonable to assume that the difference in MOR is a result of the effect of SG. To investigate this assumption, information from the linear regression analysis was used to adjust MOR for SG. Recall the relationship for MOR as a function of SG (Eq. (2)). The slope in this equation provides an estimate for change in MOR for a given change in SG (Eq. (3)). Using the known values for MOR and SG, a predicted value for MOR may be determined for a given reference SG (Eq. (4)). The reference SG was set at the overall average (0.48), and the group comparisons were made, as before, for MOR (Table 7).

$$\text{MOR} = 28.1\ \text{SG} - 0.65 \tag{2}$$

$$\frac{(\text{MOR}_{\text{predicted}} - \text{MOR})}{(\text{SG}_{\text{reference}} - \text{SG})} = 28.1 \tag{3}$$

$$\frac{\Delta\text{MOR}}{\Delta\text{SG}} = 28.1 \tag{4}$$

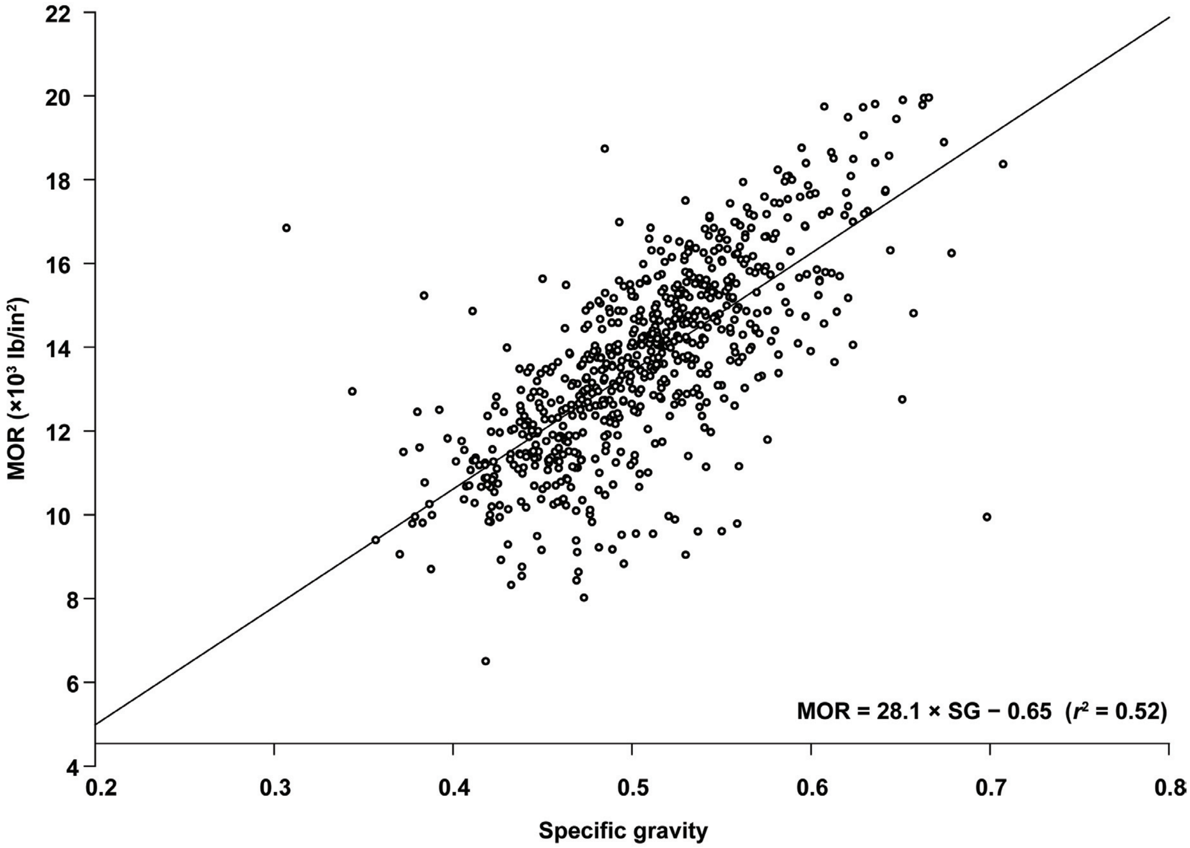

Figure 10—Small clear linear regression relationships for modulus of rupture (MOR) as a function of specific gravity.

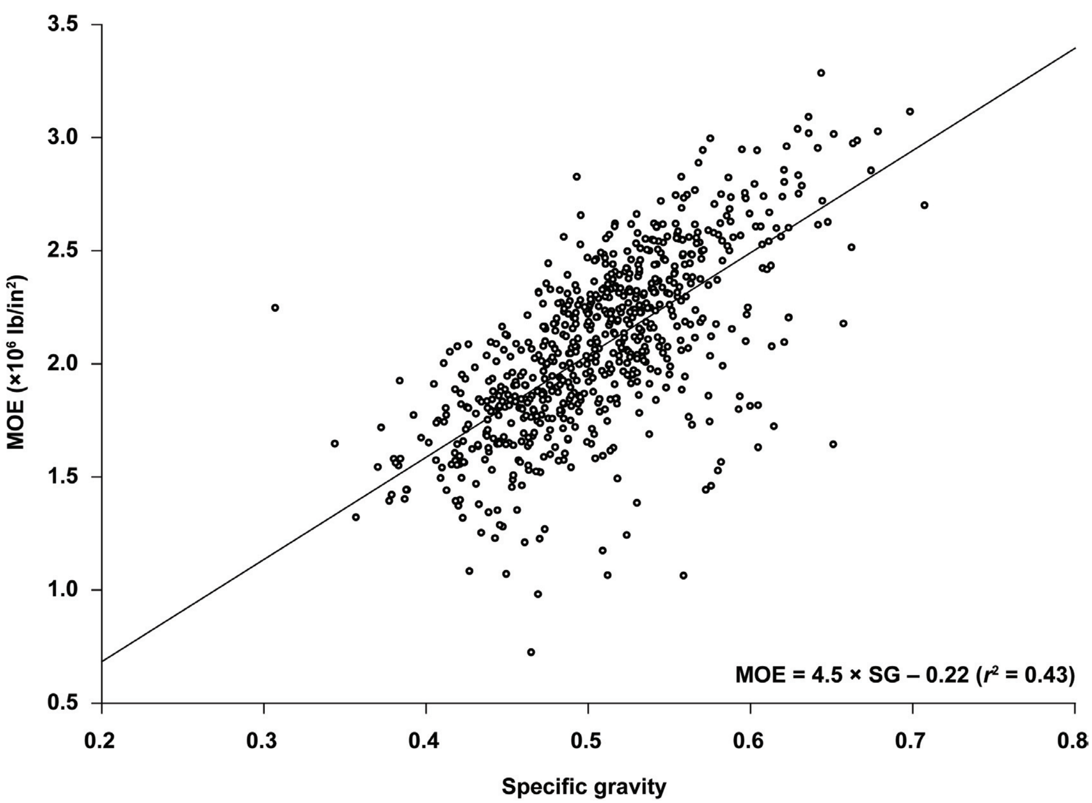

Figure 11—Small clear linear regression relationships for modulus of elasticity (MOE) as a function of specific gravity.

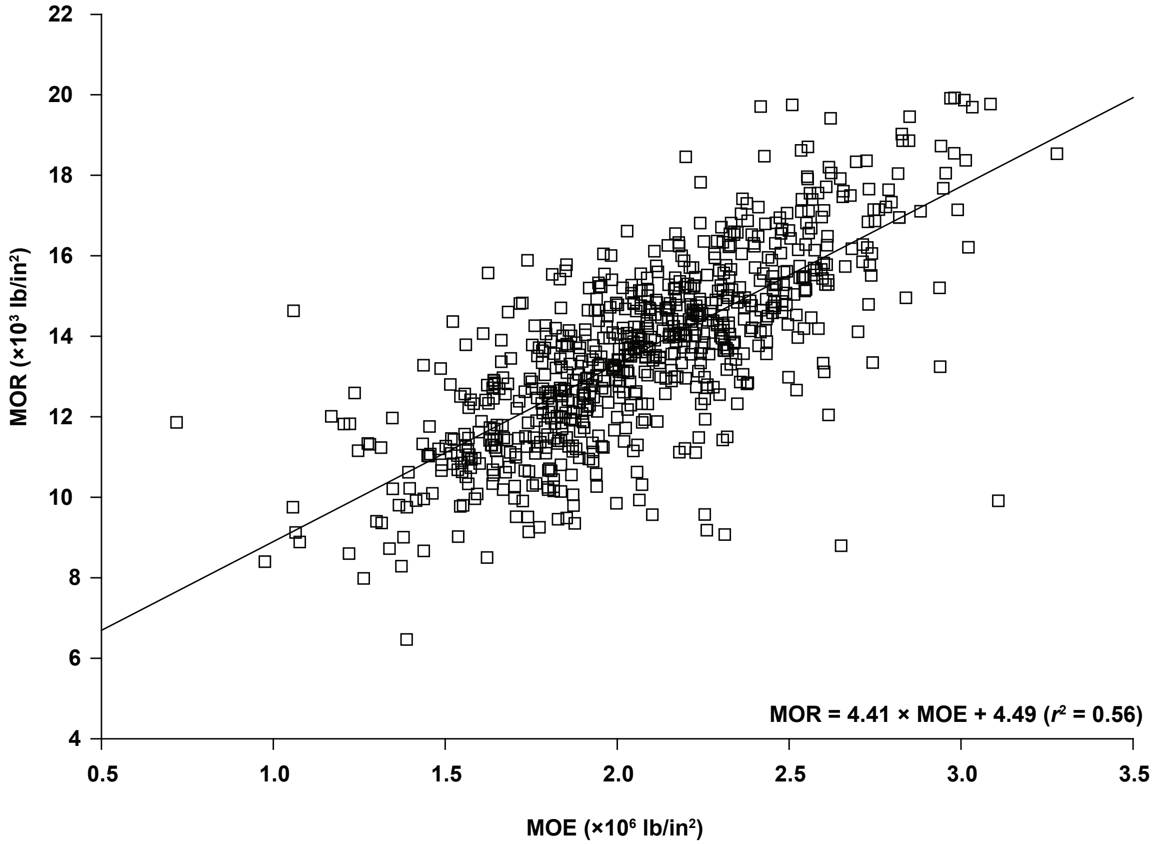

Figure 12—Small clear linear regression relationship for modulus of rupture (MOR) as a function of modulus of elasticity (MOE).

Table 4—Small clear modulus of rupture (MOR) group comparisons

		MOR ($\times 10^3$/in^2)			
Size	Location	Mean	COV[a]	No.	Grouping[b]
2 by 10	Oakland	14.21	15.6	307	A
2 by 6	Oakland	14.16	13.8	54	A
2 by 6	Washington	13.78	15.0	53	A, B
2 by 8	Fort Ord	13.49	21.9	59	A, B
2 by 10	Minnesota	13.17	15.7	116	A, B
2 by 8	Fort Ord	12.91	16.6	32	B
2 by 6	Washington	12.77	15.9	128	B

[a] Coefficient of variation.
[b] Tukey grouping. Means with the same letter are not significantly different (95% confidence).

Table 5—Small clear modulus of elasticity (MOE) group comparisons

		MOE ($\times 10^6$ lb/in^2)			
Size	Location	Mean	COV[a]	No.	Grouping[b]
2 by 10	Oakland	2.21	15.9	307	A
2 by 6	Oakland	2.12	16.3	54	A, B
2 by 6	Washington	2.08	21.5	53	A, B
2 by 10	Minnesota	2.03	16.2	116	A, B, C
2 by 8	Washington	1.96	18.7	128	B, C, D
2 by 8	Fort Ord	1.88	23.5	59	C, D
2 by 6	Fort Ord	1.79	16.5	32	D

[a] Coefficient of variation.
[b] Tukey grouping. Means with the same letter are not significantly different (95% confidence).

The result of this analysis of covariance indicates that MOR values do not vary significantly as a result of location and differences in SG can account for differences in MORs for the small clear specimens. Overall, the SGs for the Oakland groups were higher than average, whereas the Minnesota, 2 by 6 Washington, and 2 by 8 Fort Ord groups were average, and the 2 by 6 Fort Ord and 2 by 8 Washington groups were below average.

Full-Size Lumber

Knowing that the small clear data exhibit properties comparable with historical values, the next step is to examine data from the full-size bending tests. The first data to be presented are a statistical summary of 991 pieces of Douglas-fir and larch (Table 1) for the three sizes and two visual grades tested. Examination of these data will determine if the size equations developed for new lumber apply to reclaimed lumber. If so, the data can be adjusted to a single size and

Table 6—Small clear specific gravity (SG) group comparisons

Size	Location	SG (12%) Mean	COV[a]	No.	Grouping[b]
2 by 10	Oakland	0.492	10.0	290	A
2 by 6	Oakland	0.491	10.1	43	A
2 by 8	Fort Ord	0.488	13.5	56	A
2 by 10	Minnesota	0.485	11.5	106	A
2 by 6	Washington	0.480	8.8	53	A, B
2 by 8	Washington	0.456	11.0	128	B, C
2 by 6	Fort Ord	0.445	13.0	32	C

[a] Coefficient of variation.
[b] Tukey grouping. Means with the same letter are not significantly different (95% confidence).

Table 7—Small clear modulus of rupture (MOR) group comparisons adjusted by specific gravity

Size	Location	MOR ($\times 10^3$ lb/in^2) Mean	COV[a]	No.	Grouping[b]
2 by 6	Fort Ord	13.88	18.3	32	A
2 by 10	Oakland	13.86	11.4	290	A
2 by 6	Washington	13.78	10.1	53	A
2 by 6	Oakland	13.75	9.88	43	A
2 by 8	Washington	13.44	9.3	128	A
2 by 8	Fort Ord	13.37	13.9	56	A
2 by 10	Minnesota	13.1	12.8	106	A

[a] Coefficient of variation.
[b] Tukey grouping. Means with the same letter are not significantly different (95% confidence).

Table 8—Statistical summary for reclaimed No. 2 lumber, Douglas-fir and larch

	2 by 6				2 by 8				2 by 10			
Property (units)	No.	Mean	5th%	COV[a]	No.	Mean	5th%	COV	No.	Mean	5th%	COV
MOR ($\times 10^3$ lb/in^2)	107	5.28	2.30	41.7	241	4.79	2.08	43.4	93	4.04	1.68	42.4
MOE ($\times 10^6$ lb/in^2)	103	1.79	1.16	23.3	43	1.69	1.07	18.8	78	1.78	1.12	21.9
Specific gravity	107	0.50	0.41	11.3	241	0.48	0.40	10.7	93	0.49	0.40	12.9
Moisture content (%)	107	12.3	10.3	7.6	241	11.7	9.7	10.1	93	11.4	8.5	11.5

[a] Coefficient of variation.

Table 9—Statistical summary for reclaimed Select Structural (SS) lumber, Douglas-fir and larch

	2 by 6				2 by 8				2 by 10			
Property (units)	No. 2	Mean	5th%	COV[a]	No. 2	Mean	5th%	COV	No. 2	Mean	5th%	COV
MOR ($\times 10^3$ lb/in^2)	96	7.03	3.53	31.5	163	6.11	2.96	37.1	291	5.65	2.82	31.8
MOE ($\times 10^6$ lb/in^2)	94	2.13	1.46	18.3	125	1.90	1.35	18.2	254	2.19	1.57	17.5
Specific gravity	96	0.52	0.42	10.9	163	0.49	0.40	13.2	291	0.51	0.42	10.8
Moisture content (%)	96	11.8	10.3	8.5	163	13.2	11.6	5.7	291	10.4	8.6	9.9

[a] Coefficient of variation.

combined for broader analyses. Also, the effect of including other species into these data will be examined. Values of interest included the number of samples used in the calculation, the sample mean, the 5th percentile estimate (at a 75% lower confidence level) and the coefficient of variation (Tables 8 and 9).

Property Comparisons

Tables 8 and 9 tabulate the various properties for the different size-grade lumber groups. Figures 13 and 14 provide a visual measure of the effect of member size, grade, and the effect of SG and MOE on MOR. The graphs are two-variable scatter plots for each size-grade of tested lumber and include bi-directional 95% confidence interval bars.

A grade effect on MOE for all sizes is revealed in Figure 13 and indicates that within a grade, the MOEs are statistically the same for the 2 by 6 and 2 by 10 sizes. However, the 2 by 8 size is lower for the SS grade and tends to be lower, though not statistically different, than the No. 2 grade. The lower SG for the 2 by 8 Washington group drives down the stiffness within each grade of the overall 2 by 8 group and causes a slightly lower MOR for the SS grade (Fig. 14). The previous distributions show that the higher grade 2 by 6 and 2 by 10 groups had slightly larger SGs, a result of a larger number of Oakland pieces within those groups.

Distributions

As expected, the distributions of MOR for each size-grade exhibit non-normal distribution characteristics (Fig. 15). Size effect is illustrated by the shift in curves.

The SG distributions exhibit relatively normal characteristics (Fig. 16). The distributions for all the No. 2 sizes and the 2 by 8 SS groups appear to be the same shape. The 2 by 6 and 2 by 10 SS groups are shifted to the right,

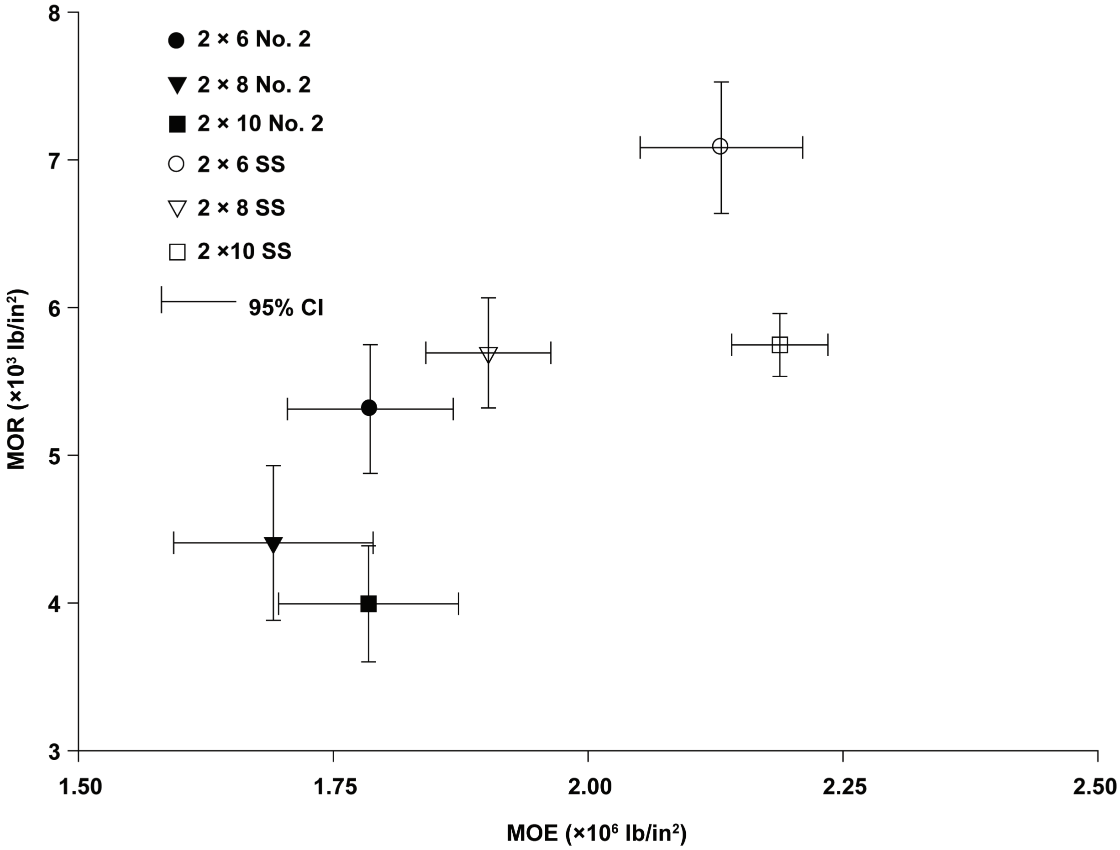

Figure 13—Modulus of elasticity (MOE) compared with modulus of rupture (MOR) plot of averages by size and grade. CI is confidence interval.

suggesting greater SG values. This can be explained because a larger percentage of the data within these two SS groups came from Oakland, where SGs were found to be higher (Table 6). Modulus of elasticity distributions show the same trend as for SG and for the same reason (Fig. 17).

Size Effect

Lumber testing has historically shown that as depth of a bending member increases, MOR decreases (Bohannan 1966). This size effect for the reclaimed lumber tested is shown in Figure 18. A multiple comparison test was performed and indicated that for the No. 2 grade, average 2 by 8 MOR is statistically different than the 2 by 10 MOR, but not for the 2 by 6 MOR. The reverse is indicated for the SS grade, where the average 2 by 8 MOR is statistically different than the 2 by 6 MOR, but not different than the 2 by 10 MOR.

Linear regressions were determined for each grade relating mean MOR values to the actual member depth (Table 10, Fig. 19). This was done to compare the size relationship for MOR means and the 5th percentile estimate at the lower 75% confidence level. The 5th percentile estimate values are important, as ASTM D 1990 specifies this is the typical statistical value used to develop design properties (ASTM 2000). As indicated in Figure 19, the linear fits for each grade are nearly parallel at both the mean and 5th percentile levels.

The overall consistency of MOR compared with size model of both size and grade suggests that no major irregularities exist in the overall data set. Despite the disproportioning of sources within some of the size-grade cells, the MOR values are not appreciably affected in this overall model.

More common size models take on the form of a power relationship (equation (5.1), ASTM D 245). The size relationship for MOR from ASTM D 1990 takes on a slightly different form (Eq. (5)). This model will be compared to a nonlinear regression for the reclaimed lumber data of the same form. Note that the testing was performed at a span-to-depth ratio of 17:1 (Eqs. (6) and (7)). Plugging Eq. (6) and Eq. (7) into Eq. (5) and reducing and combining terms gives Eq. (8). This equation can be expanded into Eq. (9) and collecting terms written as Eq. (10). The resulting constant *C* (Eq. (11)) is a reference point calculated from the reclaimed MOR and depth means given in Tables 8 and 9 for each grade. Table 11 indicates the calculation of *C* using a weighted average to combine sizes. The constant is very consistent between different sizes within the SS grade, whereas the 2 by 8 value is higher than the 2 by 6 and 2 by 10 within the No. 2 grade.

$$\mathrm{MOR}_2 = \mathrm{MOR}_1\left(\frac{d_1}{d_2}\right)^{0.29}\left(\frac{L_1}{L_2}\right)^{0.14}\left(\frac{T_1}{T_2}\right)^{0} \qquad (5)$$

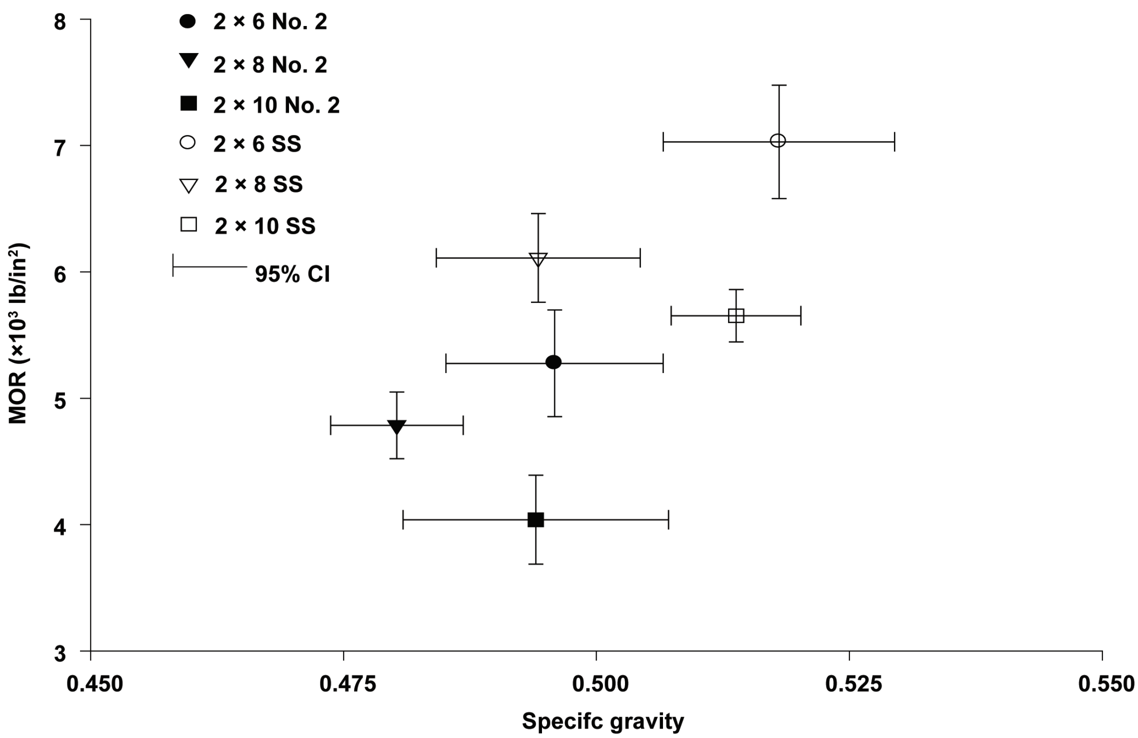

Figure 14—Specific gravity (SG) compared with modulus of rupture (MOR) plot of averages by size and grade. CI is confidence interval.

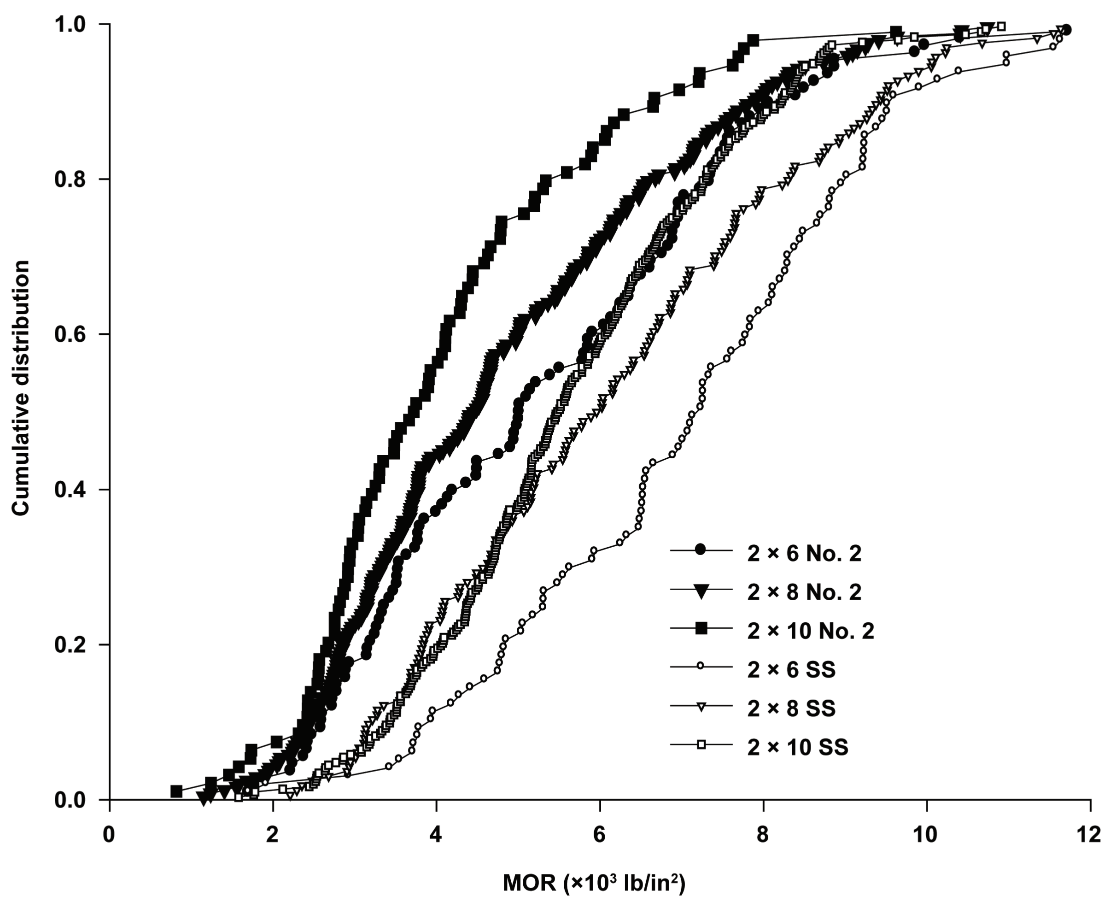

Figure 15—Modulus of rupture (MOR) cumulative distributions by size and grade.

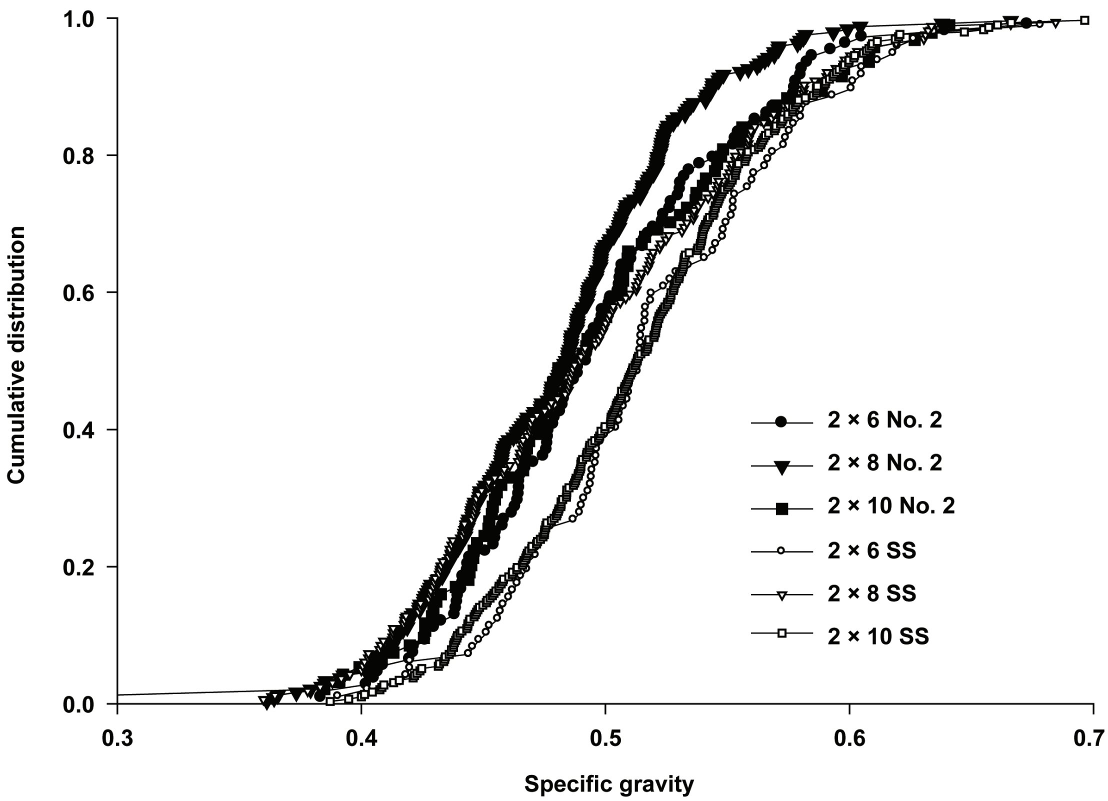

Figure 16—Specific gravity (SG) cumulative distributions by size and grade.

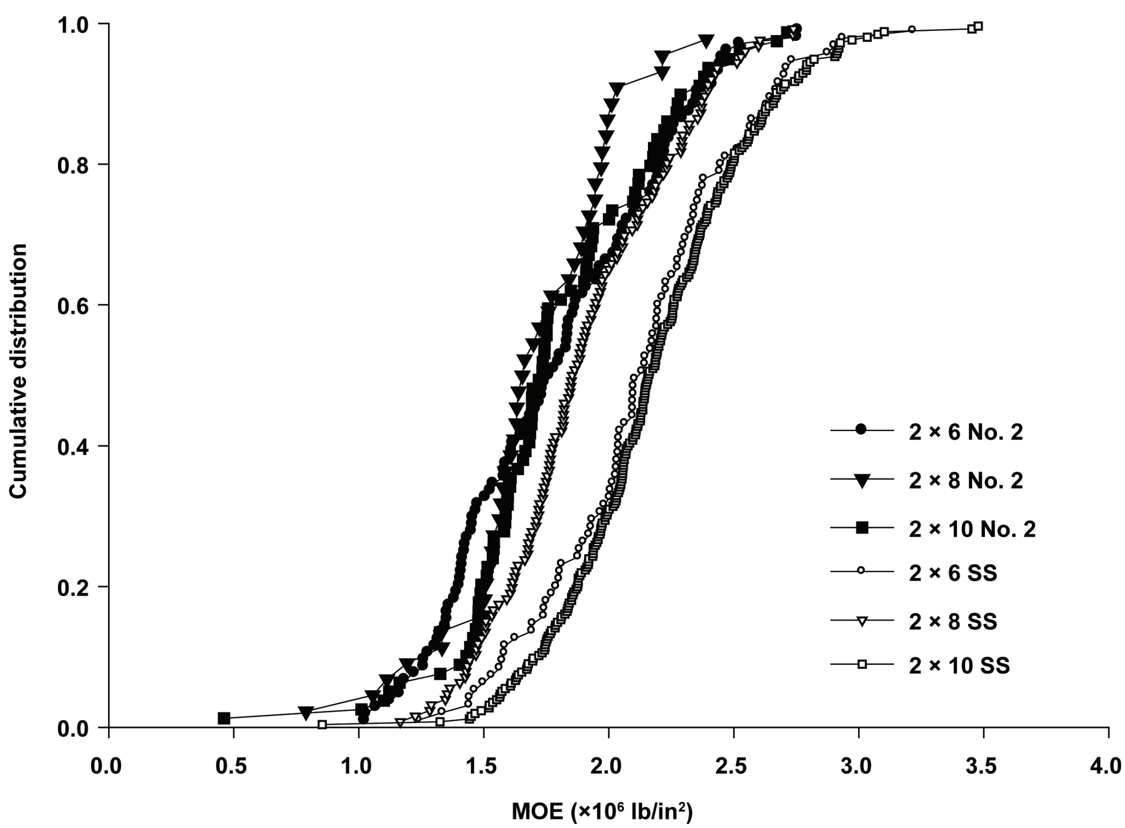

Figure 17—Modulus of elasticity (MOE) cumulative distributions by size and grade.

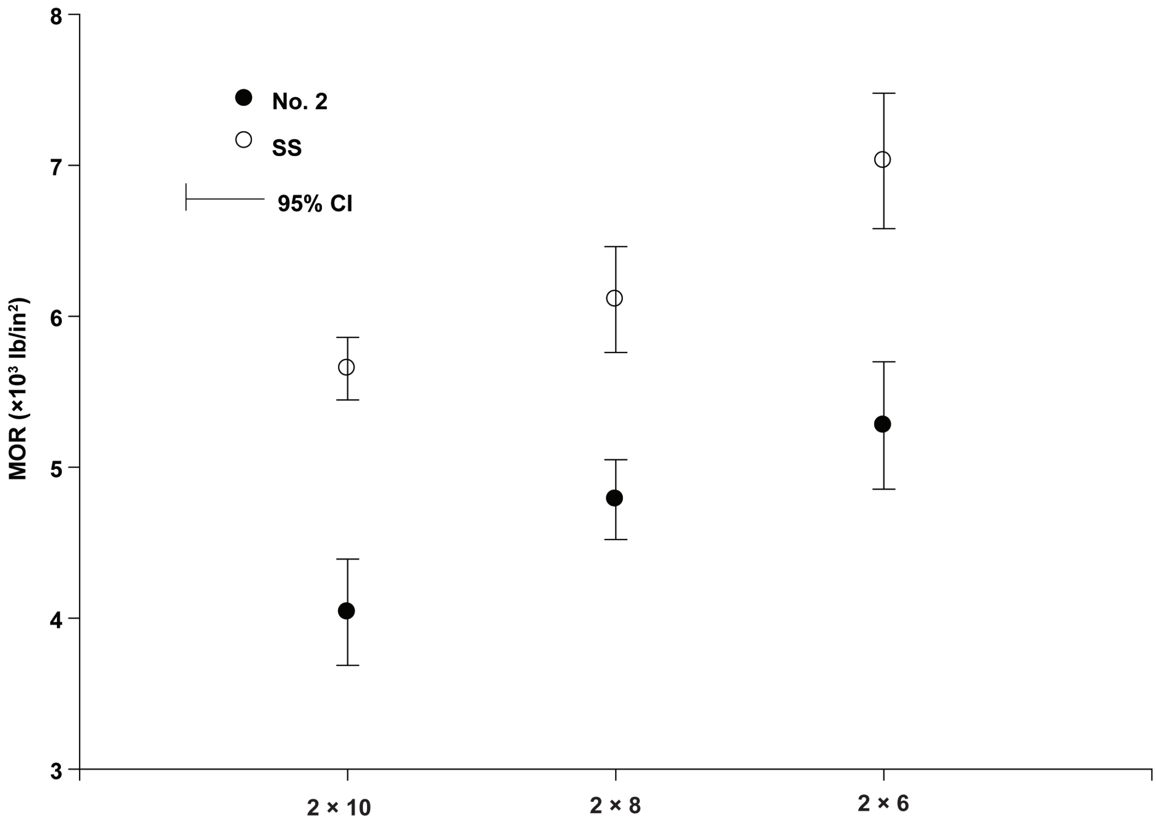

Figure 18—Size effect on modulus of rupture (MOR) for No. 2 and SS grades. CI is confidence interval.

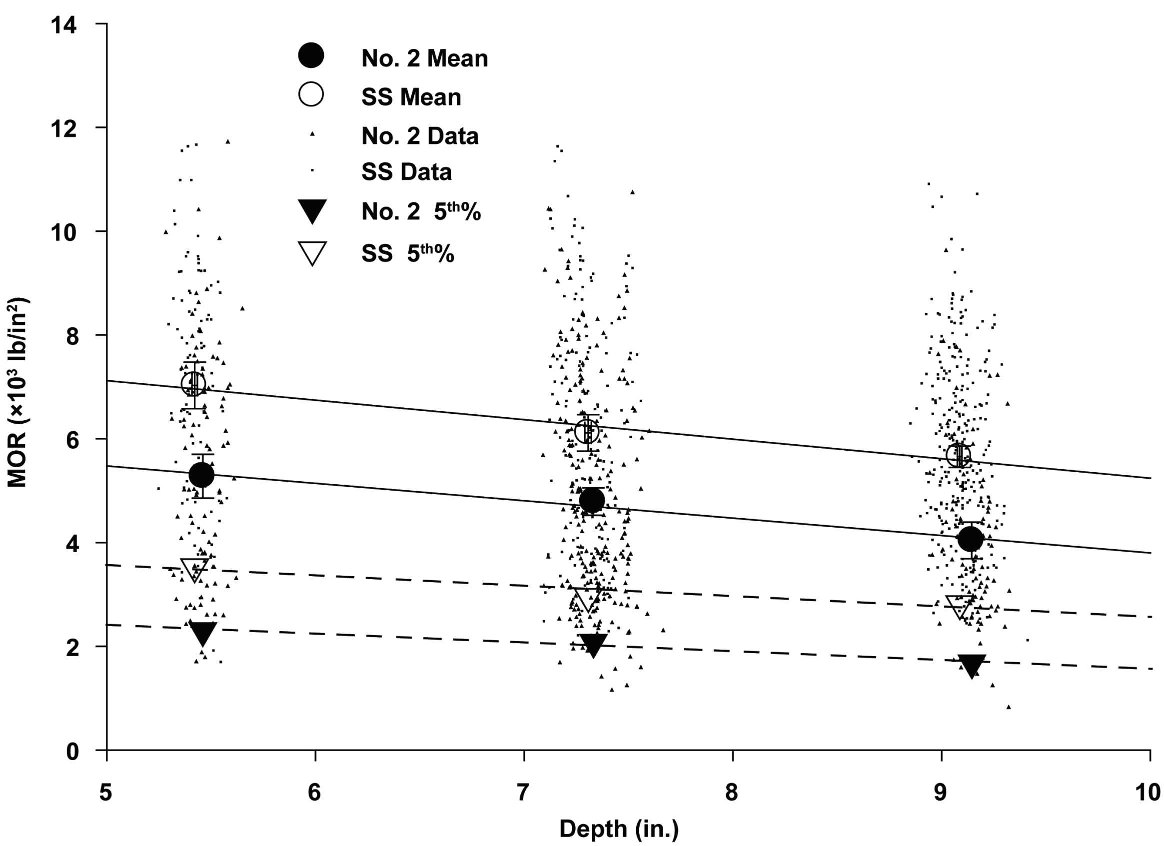

Figure 19—Size effect model for mean and 5th percentile characteristic modulus of rupture (MOR) values for No. 2 and SS grades.

where

MOR_1 is modulus of rupture at volume 1,
MOR_2 modulus of rupture at volume 2,
d_1 depth at MOR_1,
d_2 depth at MOR_2,
L_1 length at MOR_1,
L_2 length at MOR_2,
T_1 thickness at MOR_1, and
T_2 thickness at MOR_2

$$L_1 = 17\,d_1 \quad (6)$$

$$L_2 = 17\,d_2 \quad (7)$$

$$MOR_2 = MOR_1 \left(\frac{d_1}{d_2}\right)^{0.43} \quad (8)$$

$$MOR_2 = MOR_1\,(d_1)^{0.43}\,(d_2)^{-0.43} \quad (9)$$

$$MOR_2 = C(d_2)^{-0.43} \quad (10)$$

$$C = MOR_1(d_1)^{0.43} \quad (11)$$

Nonlinear regression curves were then fitted to the No. 2 and SS data groups and plotted in conjunction with the derived ASTM D 1990 (Eq. (10)). As shown in Figure 20, the curves for the reclaimed lumber data match the ASTM equations quite well. This indicates that the size-effect equations established for new lumber are applicable to reclaimed Douglas-fir lumber.

Comparison to Other Data

As was done with the small clear data, it is logical to compare the full-size reclaimed lumber data to existing mill lumber data sets. As explained earlier, the major difference between the lumber resource produced in a sawmill and the reclaimed lumber resource is the presence of damage in the reclaimed lumber. Ideally, we would like to quantify the effects of this damage on lumber properties. From a research standpoint, the ideal way to do this would have been to set aside, at the time of construction (in this case, 1942), a grade- and MOE-matched sample of lumber for future testing. Unaffected by the many years of service life as well as the damage imposed by construction and deconstruction, this sample would serve as a control to the lumber tested in this study and provide a means to quantify the damage variable. Unfortunately, no such sample exists. So, the best we can do is to compare the reclaimed lumber data to existing lumber data. The in-grade program (Green and Evans 1988) provides the most logical data set for this comparison.

In-Grade Comparison

Table 12 shows the SG data collected during the in-grade program (Green and Evans 1989). Specific gravity information was not available for all of the sizes and grades of interest here. In fact, of the six size–grade combinations, SG information only exists for one. The average SG for all sizes and grades of reclaimed Douglas-fir tested in this study was 0.498, which is very close to the in-grade average of 0.494.

Table 10—Modulus of rupture (MOR) as a function of size linear regression relationships based on means and 5th percentile estimate values

MOR value ($\times 10^3$ lb/in^2)	Grade	A_1 (($\times 10^3$ lb/in^2)/in)	A_0 ($\times 10^3$ lb/in^2)
Mean	No. 2	– 0.34	7.15
	SS	– 0.38	9.00
5th percentile	No. 2	– 0.17	3.25
	SS	– 0.20	4.52

From this standpoint, the reclaimed lumber resource appears to be very similar to the wood resource tested between 1977 and 1987 (Green and Evans 1989). The next step is to see how strength and stiffness compare.

All in-grade lumber was tested in third-point bending at a span-to-depth ratio of 17:1; however, deflections were measured at the load points. For the reclaimed data, deflections were measured at the center point of the member relative to the supports. A correction factor of 0.993, based on ASTM D 2915 and ASTM D 2915-03 (2000) was used to correct the difference between the two data sets; however, the effect on summary statistics was insignificant. Because the in-grade lumber was field tested, MC and temperature could not be controlled. However, these data were recorded, and adjustments (ASTM D 1990) were made to a reference MC of 12% and a temperature of 75°F, the same as the test conditions for the reclaimed lumber. The MOE and MOR are reported to reflect those conditions (Green and Evans 1988) Table 13 compares the mean MOR and MOE values for the reclaimed data to the in-grade data for the sizes and grades of interest. Note that Table 13 does not contain a comparison for the 2 by 6 data, as 2 by 6s were not tested within the in-grade program. Average MCs and specific gravities were very similar to in-grade values for the individual size-grade groups.

The trends in MOE and MOR are quite interesting. The percentage difference column of Table 13 shows that MOR is roughly 26% lower for the reclaimed lumber. The higher grades also show a greater difference than the lower grades. The question is why the bending strength is lower. Based on the small clear results, it is not likely that the wood experienced some degradation on the microscopic level from load duration, temperature, or moisture exposure. Has damage from drying, nail holes, or the deconstruction process on the macroscopic level reduced bending strength?

Conversely, opposite trends exist for MOE. For all but one of the size-grade groups (and that group is only 43 pieces), the reclaimed lumber MOEs are higher by approximately 9% overall. This is consistent with what was seen in the small clear data (Table 3).

In summary, based on the comparison to the in-grade data, the reclaimed lumber resource is very similar for SG. Despite this, MOR is approximately 26% lower and stiffness is greater by about 9%.

Table 11—Calculation of constant *C* for size model, Eq. (11)

Grade	Nominal size	*N*	MOR ($\times 10^3$ lb/in^2)	Depth (in.)	MOR $(d)^{0.43}$ ($\times 10^3$ lb/in)
No. 2	6	107	5.28	5.46	10.95
	8	241	4.79	7.33	11.27
	10	93	4.04	9.15	10.46
	Weighted average =				11.02
SS	6	96	7.03	5.42	14.53
	8	163	6.11	7.31	14.37
	10	291	5.65	9.09	14.60
	Weighted average =				14.52

Table 12—In-grade Douglas-fir specific gravity information

Size	Grade[a]	No.	Mean SG[b]
2 by 4	SS	817	0.51
	No. 2	767	0.49
	No. 1	381	0.48
	Construction	275	0.48
	Standard	273	0.48
	Utility	273	0.47
	Stud	227	0.49
2 by 8	No. 2	972	0.50
All	All	3985	0.49

[a] Based on West Coast Lumber Inspection Bureau grading rules Standard 17.
[b] SG is specific gravity. The mean is based on oven-dry weight and volume.

Table 13—Comparison of in-grade and reclaimed data for full size lumber, Douglas-fir only

			Reclaimed				In-grade[b]				Percentage difference[c]	
Size	Grade[a]	Property (units)	*N*	Mean	5th%[d]	COV[e]	*N*	Mean	5th%	COV	Mean	5th%
2 by 8	No. 2	MOR ($\times 10^3$ lb/in^2)	241	4.79	2.08	43	1964	6.25	2.47	42.7	23.4	15.9
		MOE ($\times 10^6$ lb/in^2)	43	1.68	1.07	19	1964	1.62	1.02	25.1	– 4.1	– 4.5
		Moisture content (%)	241	11.7	9.7	10						
		Specific gravity	241	0.48	0.40	11						
	SS	MOR ($\times 10^3$ lb/in^2)	163	6.11	2.96	37	493	8.48	4.09	30.4	28.0	27.6
		MOE ($\times 10^6$ lb/in^2)	125	1.90	1.35	18	493	1.91	1.31	20.7	0.4	–3.9
		Moisture content (%)	163	13.2	11.6	6						
		Specific gravity	163	0.49	0.40	13						
2 by 10	No. 2	MOR ($\times 10^3$ lb/in^2)	93	4.04	1.68	42	388	5.45	2.16	46.3	25.9	22.1
		MOE ($\times 10^6$ lb/in^2)	78	1.78	1.12	22	388	1.59	1.02	24.7	– 12.2	– 9.5
		Moisture content (%)	93	11.4	8.6	11						
		Specific gravity	93	0.49	0.40	13						
	SS	MOR ($\times 10^3$ lb/in^2)	291	5.65	2.82	32	414	7.84	3.83	29.8	27.9	26.2
		MOE ($\times 10^6$ lb/in^2)	254	2.19	1.57	18	414	1.92	1.31	20.0	– 13.9	– 19.5
		Moisture content (%)	291	10.4	8.6	10						
		Specific gravity	291	0.51	0.42	11						

[a] Based on West Coast Lumber Inspection Bureau grading rules Standard 17.
[b] Data adjusted to 12% MC, 75° F, and tested at 17:1.
[c] (in-grade – reclaimed) / (in-grade).
[d] 5th percentile nonparametric estimate.
[e] Coefficient of variation.

Analysis of Full-Size Lumber by Size and Grade

Location and Member Type

In this section, data from testing full-size lumber will be reviewed, with a specific look at the effects of location, member type, and damage on bending strength and stiffness.

Based on previous analysis, it was apparent that lumber size and grade have a significant effect on MOR. For this reason, the data were sorted into size-grade-location groups and pair-wise comparisons of the properties of MOR, MOE, and MC were made using a Tukey test at 95% confidence that the means are not equal. Graphs were also produced comparing average properties of MOR, MOE, and SG for the SS and No. 2 grades (Tables 14–16 and Figs. 21–26).

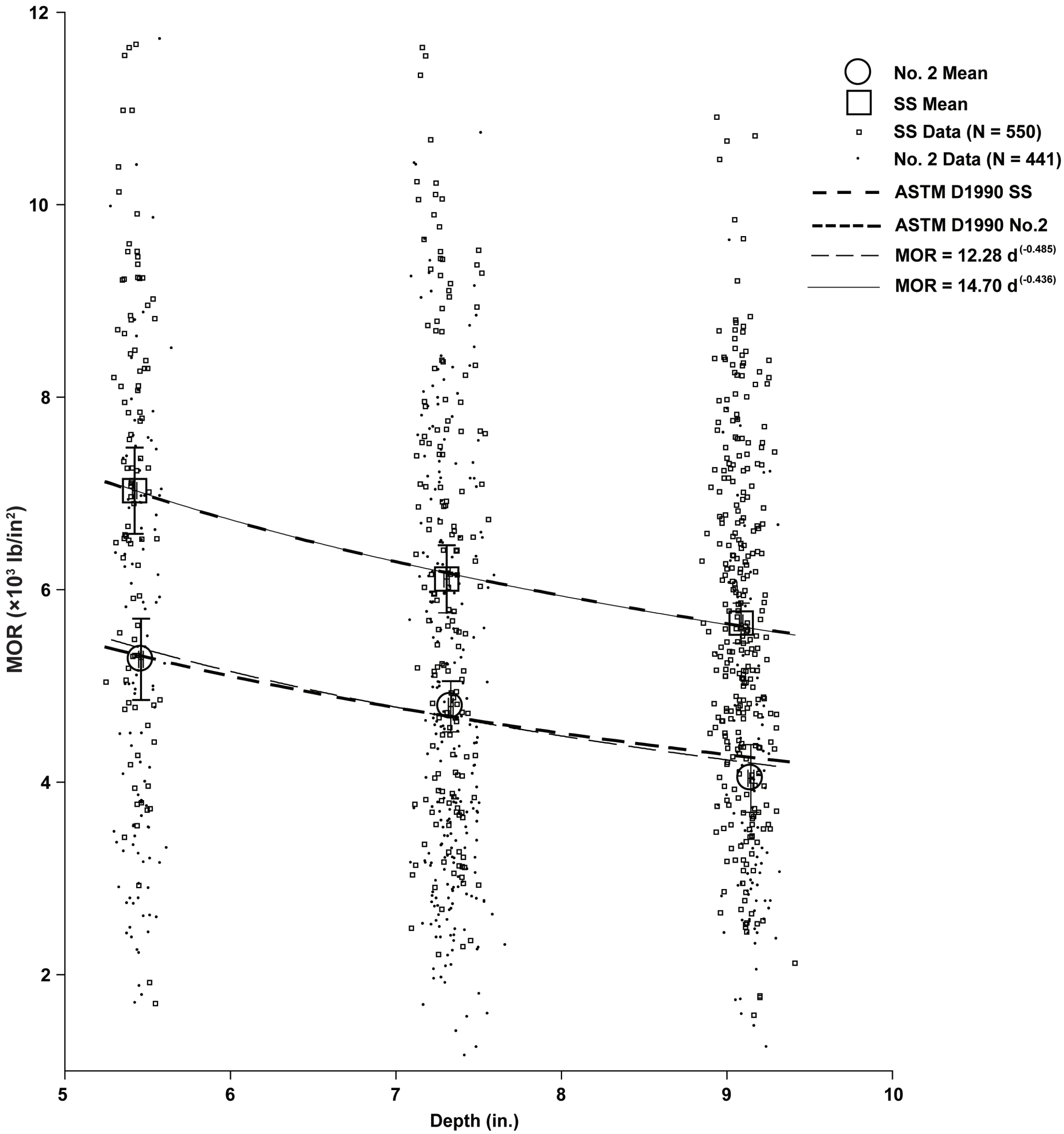

Figure 20—Nonlinear regression size model comparison to derived ASTM D1990 equation for No. 2 and SS grades (Douglas-fir).

We observed the following:

- For the 2 by 6 SS grade, no statistical difference was detected at 95% confidence between the MOR for Fort Ord and that for Washington, despite the large difference between values (Table 14).
- For the 2 by 8s, MOR was statistically the same for the No. 2 grade, but the SS grade Fort Ord boards had greater average MOR than Washington (7.55×10^3 lb/in^2 compared with 6.69×10^3 lb/in^2) (Table 15). This is likely explained by different average SGs, 0.53 compared with 0.48.
- For the 2 by 10 SS grade, Oakland exhibited greater MOR than Minnesota, likely explained by an effect of SG (Table 16).
- A statistical non-significance test showed that all three sites are similar in any pair-wise combination of MOR.
- The sample sizes for 2 by 6 SS from Fort Ord and No. 2 from Oakland and Washington are probably too small for meaningful conclusions.

Table 14—2 by 6 location comparisons

Grade	Property (units)	Fort Ord (F)			Oakland (O)			Washington (W)			Different pairs[b]
		Mean	COV[a] (%)	No.	Mean	COV (%)	No.	Mean	COV (%)	No.	
No. 2	MOR ($\times 10^3$ lb/in^2)	5.51	41.7	71	4.79	49.2	16	4.85	33.9	20	
	MOE ($\times 10^6$ lb/in^2)	1.74	23.2	71	1.96	22.8	16	1.82	23.2	16	
	Moisture content (%)	12.7	4.8	71	11.7	11.1	16	11.6	8.7	20	F & O, F & W
	Specific gravity	0.48	10.2	71	0.52	11.1	16	0.52	12.2	20	NA[b, c]
SS	MOR ($\times 10^3$ lb/in^2)	7.95	30.1	12	7.27	30.8	47	6.42	31.2	37	
	MOE ($\times 10^6$ lb/in^2)	2.13	21.6	12	2.21	17.1	47	2.03	18.1	35	
	Moisture content (%)	12.4	2.9	12	11.6	9.1	47	11.8	8.5	37	F & O
	Specific gravity	0.50	12.0	12	0.53	10.8	47	0.51	10.0	37	NA[c]

[a] Coefficient of variation.
[b] Tukey's studentized range (HSD) test at 95% or better confidence (SAS v8.2). NA is not applicable.
[c] Data summary provided for specific gravity (SG); however, a statistical comparison was not performed since SG is not well correlated to grade.

Table 15—2 by 8 location comparisons

Grade	Property (units)	Fort Ord			Washington			Different pairs[b, d]
		Mean	COV[a] (%)	No.	Mean	COV (%)	No.	
No. 2	MOR ($\times 10^3$ lb/in^2)	4.87	44.1	198	4.41	38.6	43	N
	MOE ($\times 10^6$ lb/in^2)	—	—	0	1.69	18.8	43	
	Moisture content (%)	11.5	9.6	198	12.8	6.8	43	N
	Specific gravity	0.48	11.0	198	0.48	9.6	43	NA
SS	MOR ($\times 10^3$ lb/in^2)	7.55	30.0	37	5.69	36.9	126	Y
	MOE ($\times 10^6$ lb/in^2)	—	—	0	1.90	18.2	125	
	Moisture content (%)	13.0	5.1	37	13.2	5.8	126	N
	Specific gravity	0.53	12.8	37	0.48	12.5	126	NA[c]

[a] Coefficient of variation.
[b] Tukey's studentized range (HSD) test at 95% or better confidence (SAS v8.2).
[c] NA, data summary provided for specific gravity (SG); however, a statistical comparison was not performed because SG is not well correlated to grade. N, the pairs are not statistically different; Y, a statistical comparison indicates that the pairs are different.
[d] MOE data not available for 2 × 8 Fort Ord due to error in data collection hardware.

Table 16—2 by 10 location comparisons

Grade	Property (units)	Oakland			Minnesota			Different pairs[b]
		Mean	COV[a] (%)	No.	Mean	COV (%)	No.	
No. 2	MOR ($\times 10^3$ lb/in^2)	4.07	43.1	53	3.99	41.8	40	N
	MOE ($\times 10^6$ lb/in^2)	1.84	21.1	53	1.66	22.3	25	N
	Moisture content (%)	12.0	5.8	53	10.5	13.8	40	Y
	Specific gravity	0.51	11.5	53	0.47	13.7	40	NA[b]
SS	MOR ($\times 10^3$ lb/in^2)	5.84	29.6	197	5.26	35.8	94	Y
	MOE ($\times 10^6$ lb/in^2)	2.25	17.1	197	1.99	15.0	57	Y
	Moisture content (%)	10.5	7.1	197	10.1	14.1	94	Y
	Specific gravity	0.53	9.8	197	0.49	11.4	94	NA[c]

[a] Coefficient of variation.
[b] Tukey's studentized range (HSD) Test at 95% or better confidence (SAS v8.2).
[c] NA, data summary provided for specific gravity (SG); however, a statistical comparison was not performed because SG is not well correlated to grade. N, the pairs are not statistically different; Y, a statistical comparison indicates that the pairs are different.

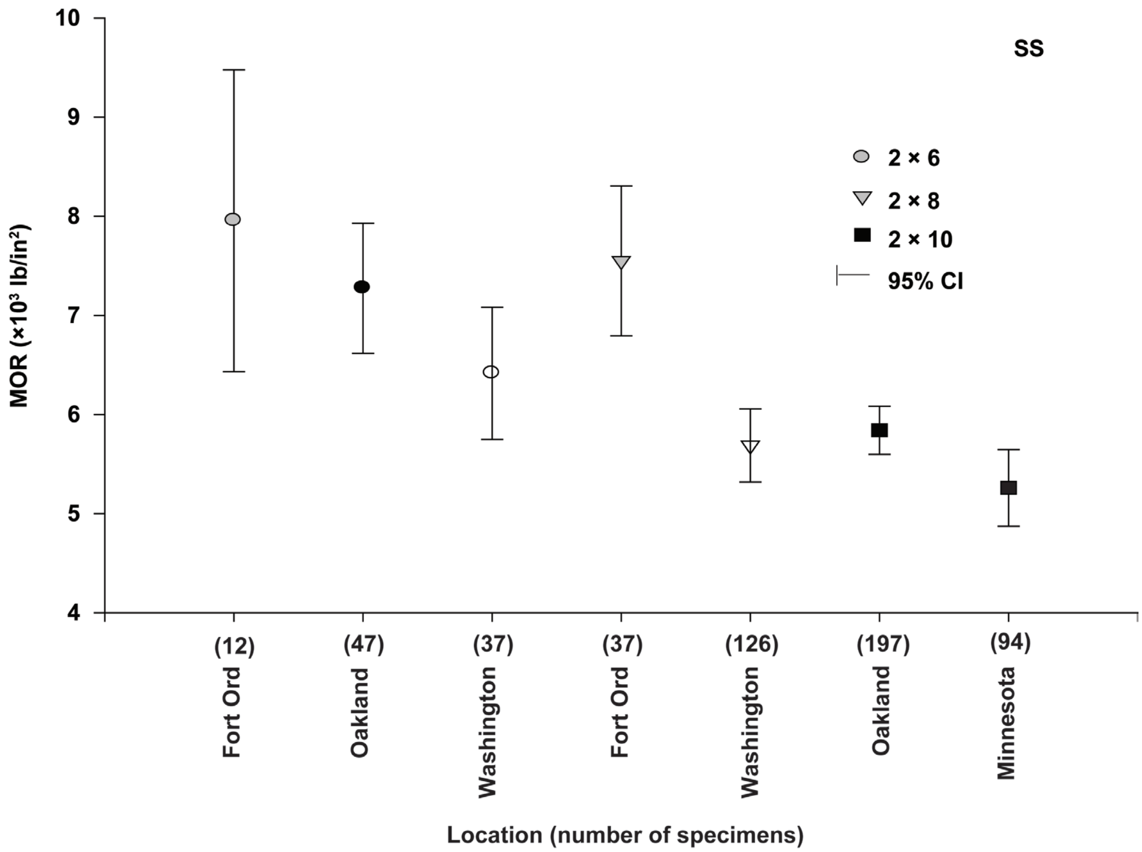

Figure 21—Modulus of Rupture (MOR) comparison by location for SS Grade. CI is confidence interval.

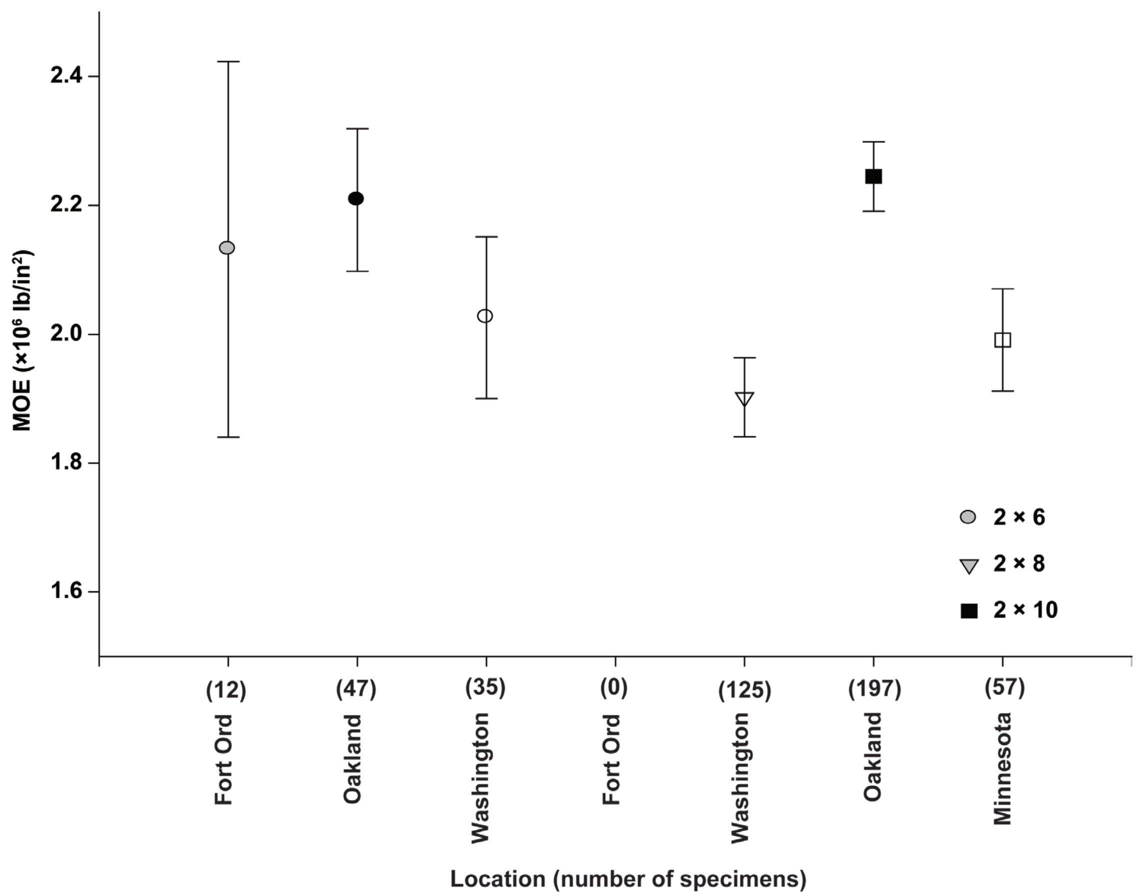

Figure 22—Modulus of elasticity (MOE) comparison by location for SS Grade.

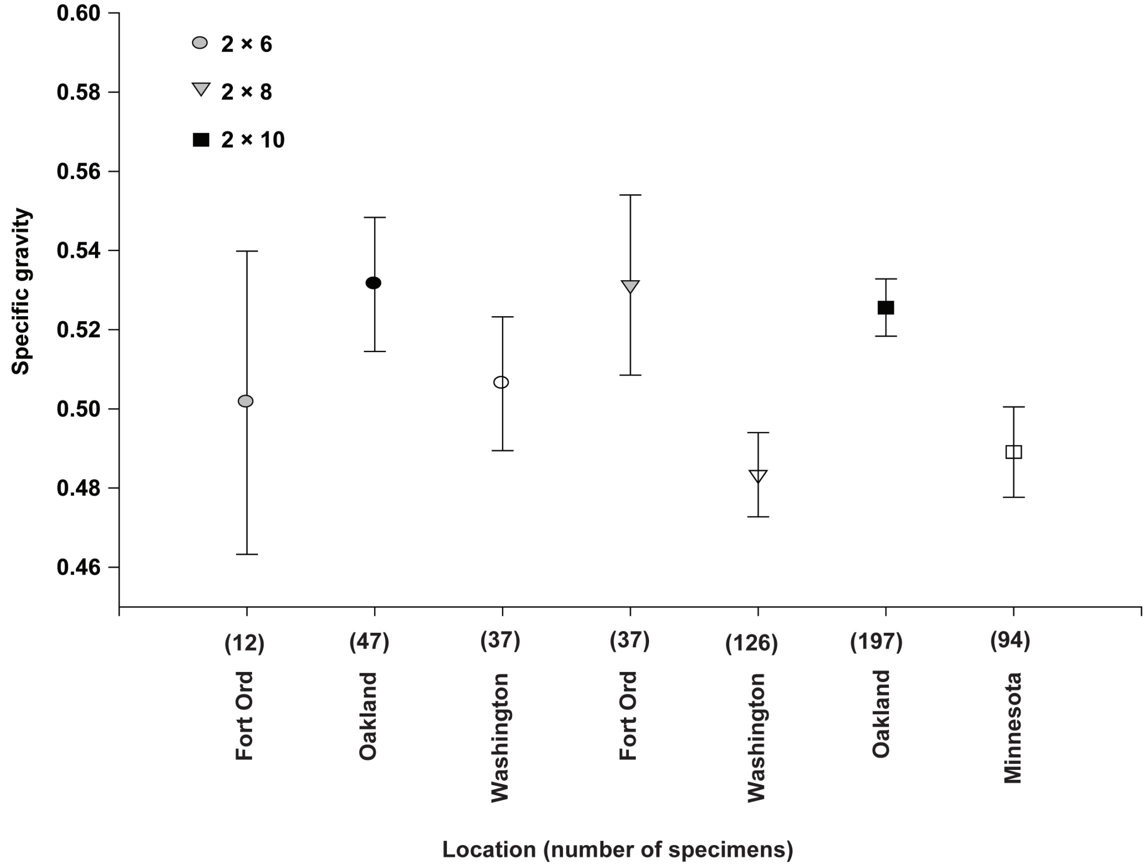

Figure 23—Specific gravity (SG) comparison by location (SS Grade).

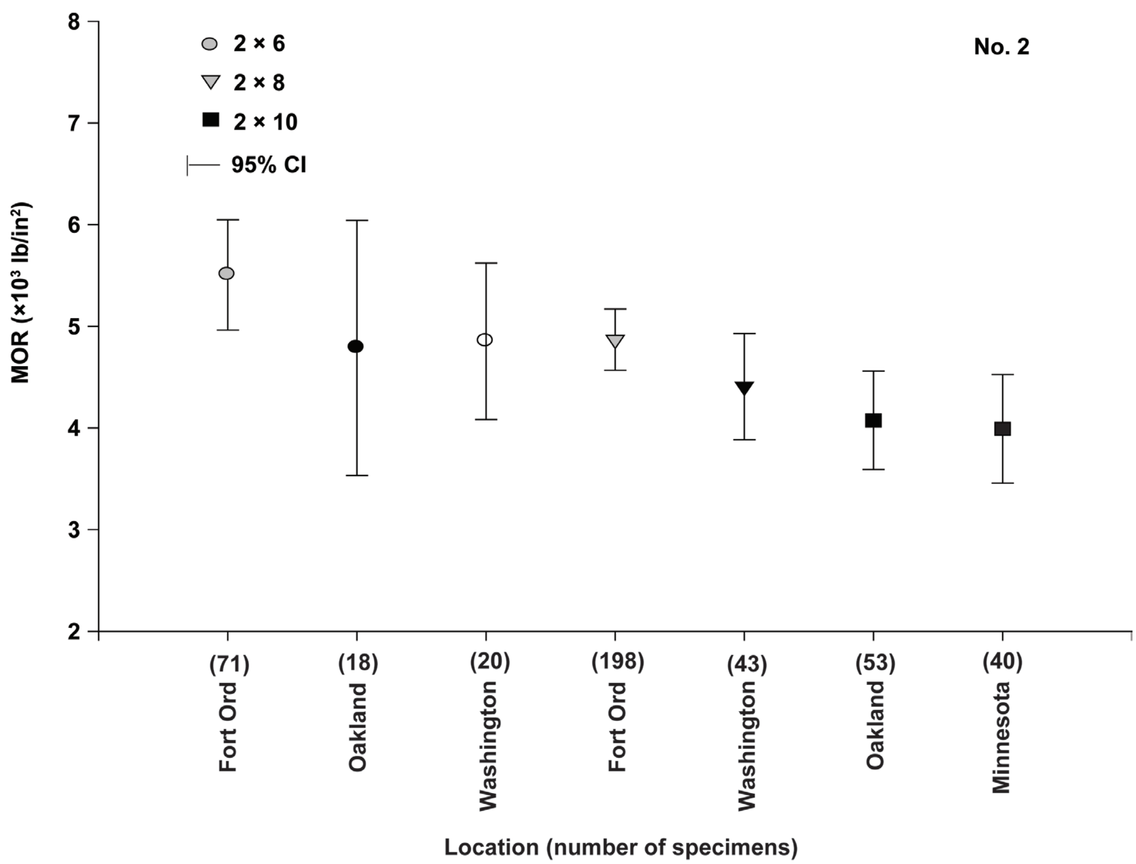

Figure 24—Modulus of rupture (MOR) comparison by location (No. 2 Grade). CI is confidence interval.

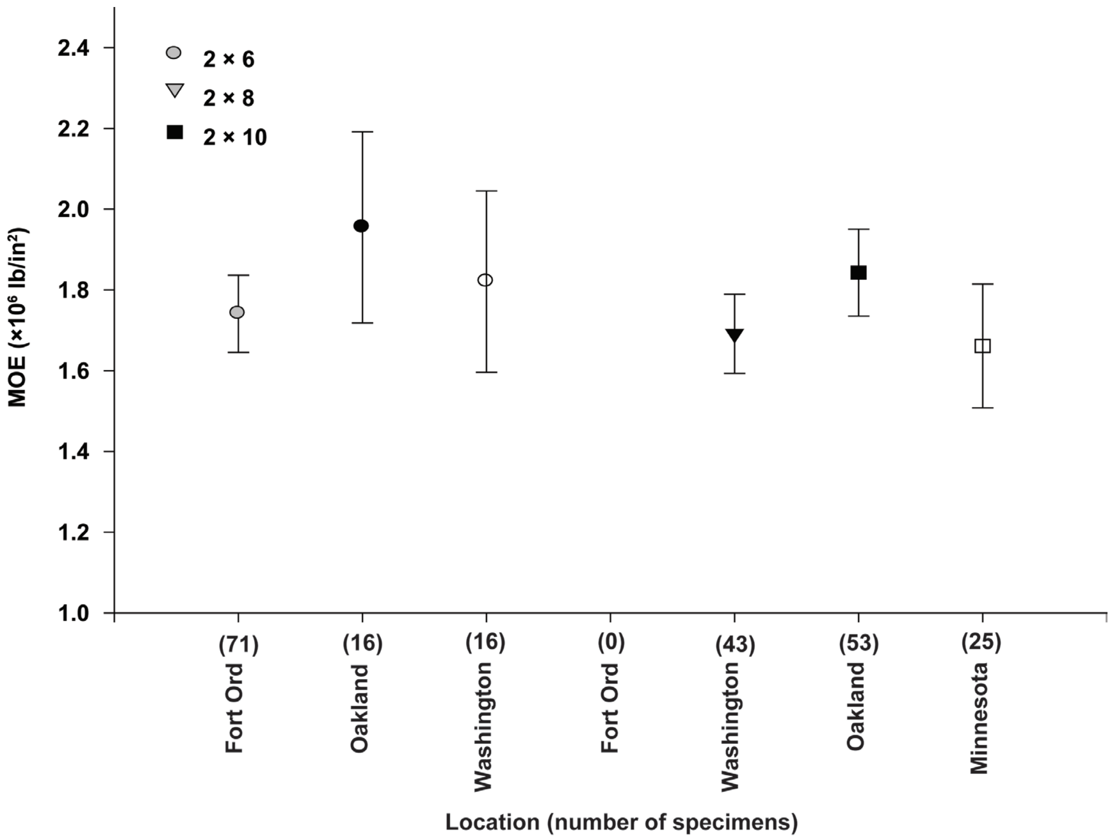

Figure 25—Modulus of elasticity (MOE) comparison by location for No. 2 Grade.

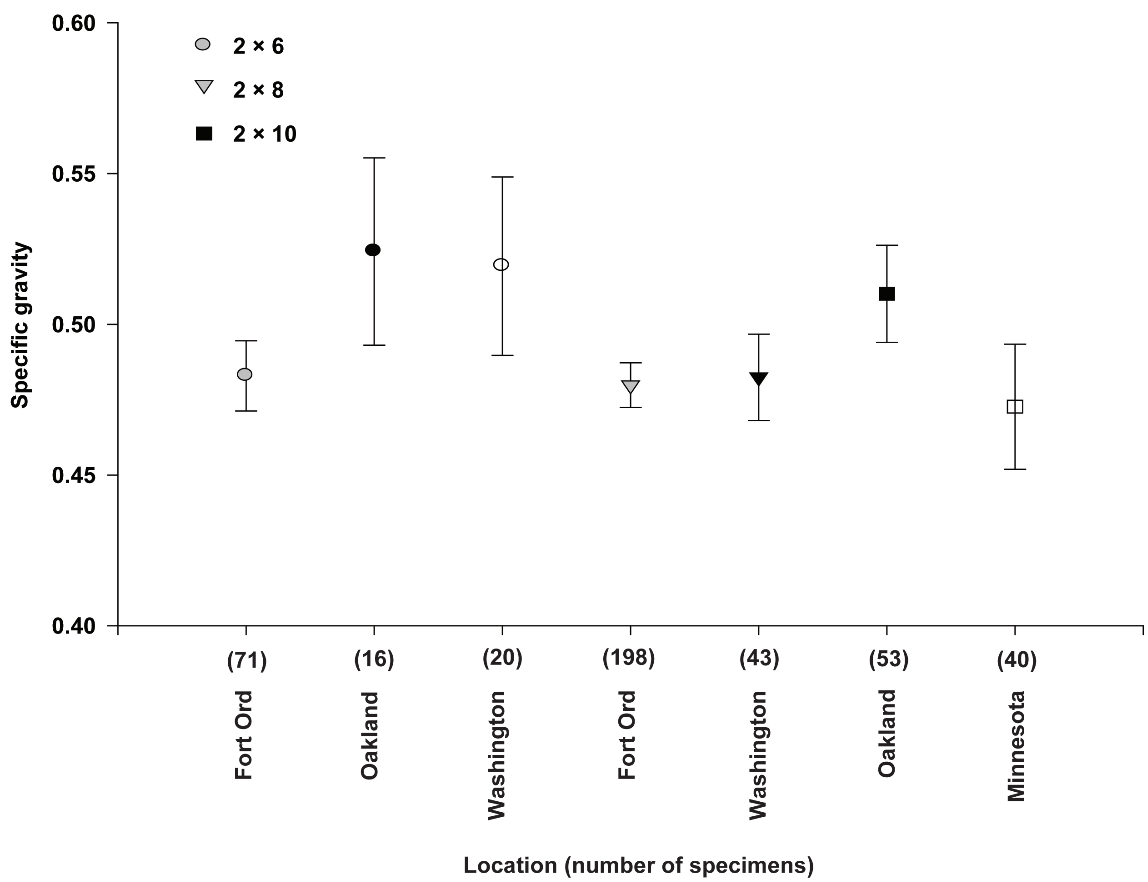

Figure 26—Specific gravity (SG) comparison by location for No. 2 Grade.

Table 17—Damage codes

General category	Code	Description
Nail hole damage	NE	Edge-nail holes (into 1-1/2-in. edge)
	NF	Face-nail holes (through board wide face)
	NT	Toenail holes (diagonal from face to edge)
Through splitting damage	SD	Through splits from drying
	SN	Through splits from nail holes
	SH	Through splits from manmade larger holes
Other mechanical damage	G	Mechanical gouging
	H	Manmade drilled holes
	CN	Cuts and notches

For the samples of lumber obtained in this study, member uses (for example, floor joist, roof joist, stud) are for the most part unique to each size-location group; thus, separate analyses for member use are moot. For example, all of the 2 by 6s from Oakland were wall studs. All of the 2 by 10s from Oakland and most of the 2 by 10s from Minnesota were roof joists; a few (12 of 125) of the Minnesota 2 by 10s were stringers. All the 2 by 6s from Fort Ord and most of the 2 by 6s from Washington were rafters; a few (6 of 57) of the Washington 2 by 6s were rafter ties or tension chords. These two groups with a slight portion of different member types did not contain enough samples to overcome variability and detect an effect of member use.

Lumber Damage

To better understand how and to what extent damage influences strength, it was necessary to categorize it. Three damage categories were developed and were based on the characteristics observed in the lumber before and after testing. These categories include (1) nail holes, (2) splitting, and (3) other mechanical damage. Specific codes to indicate each type are shown in Table 17 and were used to describe damage involved in board failures. Nail-hole damage was further defined by the geometry of the hole relative to the board face and edge. Splitting damage was further defined based on how the split was created (e.g., holes causing stress concentrations at a grain line or drying/seasoning). The last category, other mechanical damage, describes other ways the cross section of the board may have been damaged, including wane-like gouging, drilled holes, and cuts or notches (Fig. 27).

Nail Holes

Nail holes are almost always present in reclaimed lumber and can be found on every board face, including the ends. Face-nail holes (those nails found on the wide face of the lumber) are typically caused by nailing of bridging or hardware. Edge-nail holes are commonly found on joists along an entire edge of a board. Usually these nails are found along one of the two board edges and resulted from the prior attachment of a cladding surface (i.e., roof, wall, or floor). Depending on the thickness of the cladding surface, an 8d, 10d, or 12d nail was typically used. Analogous to an edge knot, edge-nail holes can potentially reduce bending strength of a bending member if the edge of the board containing the nail holes is loaded in tension. Because edge-nail holes have potentially more impact on bending strength than nail holes on other board faces, a considerable amount of analysis was performed to quantify their effect.

Edge-Nail Holes

To determine if edge-nail holes had an effect on board properties, the orientation of the edge-nail holes to testing orientation was tracked. Basically, boards with edge nails present were oriented in the test machine with the nail edge up (nail holes in compression zone) or nail edge down (nail holes in tension zone). Boards were ranked by dynamic MOE (transverse vibration) and then pairs with adjacent MOEs were assigned to alternate orientations (nail holes up or down). In addition, the nails were counted over the center third of the test span to determine the average number of holes per foot.

Edge-Nail Spacing

Some grading rules, such as WCLIB Standard No. 17, contain provisions for grading larger holes as well as smaller holes (WCLIB 2000). Depending on board size and grade, the grading rule allows a maximum size (average diameter) loose knot or hole for a particular grade. As a footnote, the grading rules allow "one hole or equivalent holes per __ ft", with the allowed length dependent on grade. Also stated is that holes shall be measured the same as knots, unless noted otherwise. These rules for allowed hole sizes are based on engineering mechanics and reduction in section modulus.

The grading rules do not contain specific guidelines for the measurement of edge-nail holes. The grade rules state that holes that extend only partially through a piece may also be designated as surface pits (see definition section 716 of grade rules). Further, nail holes would be defined as either a pin hole (if less than 1/16 in. diameter) or medium (small) hole if less than ¼ in. diameter. One could also draw a parallel to the measurement of a spike knot located along the

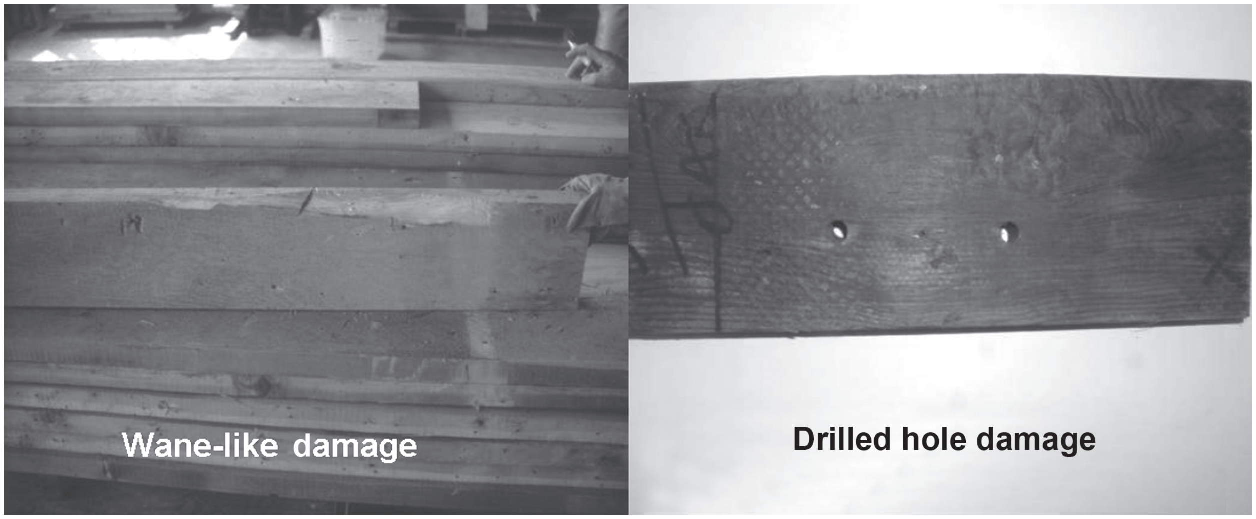

Figure 27—Examples of "other mechanical damage."

board edge, which does not appear on the three other board faces. This particular knot is defined as having a displacement equal to half its diameter (WCLIB 2000). So long as the nail does not penetrate more than half the depth of the board, measuring the displacement of the nail hole as half the diameter of the hole is conservative. This would seem a valid assumption, as typical nail-embed depths do not exceed 2-5/8 in., which is half the depth of a 2 by 6 and less than the length of a 10d nail (3 in. minus a typical sheathing thickness (3/4 in.)). We will refer to this assumption about edge-nail hole measurement as the "spike-knot analogy."

We used the spike-knot analogy to calculate an equivalent number of holes[1] per foot allowed for the two grades and three lumber sizes evaluated in this study. Two hole diameters, 1/8 in. and 3/16 in., were assumed in the analysis and represent hole sizes that might be expected in reclaimed lumber (Table 18).

Also in the far right column of Table 18 is the average nail hole spacing measured for the different lumber size-grade groups. Cumulative distributions of these measurements are shown in Figure 28. The edge-nail holes were typically around 1/8 in. in diameter[2], and sometimes a bit larger if the nails were pried laterally during removal. One particular group, Washington 2 by 6s, had noticeably smaller edge-nail holes[3]. In reality, there is some damage around nail holes from stressing, water intrusion, drying, and iron sickness that has an effect on the effective size of the hole. This is difficult to universally quantify; however, based on our visual assessment of hundreds of boards, 3/16 in. would seem a reasonable upper limit.

A comparison of the measured edge-nail hole frequencies with the allowable number of nail holes by the spike-knot analogy described above indicated that the 2 by 8 SS group satisfies the criteria, whereas the 2 by 6 SS group satisfies the nominal 1/8 in. diameter but not the upper limit 3/16 in. diameter. The 2 by 8 SS group satisfies the requirement; however, the 2 by 10 SS group exceeds the criteria (5.8 holes compared with a limit of 5.0 holes by the 1/8-in. diameter hole limitation). The 2 by 10 SS group would have met the requirements of a No. 1 grade, however (Table 18). All the No. 2 boards meet the spike-knot analogy requirements.

For two of these groups of lumber (2 by 8s from Washington and 2 by 10s from Oakland), the grader made a blanket statement that the SS grade boards with edge-nail holes should probably be downgraded to No. 2. It was the grader's opinion that the edge-nail holes over a specific length of board could be added up to determine an equivalent knot size and that knot size would determine grade. Though grading is not an exact science and is based on experience, it appears that the grader was correct in suggesting the downgrade; however, the above analysis suggests that a downgrade to No. 1 is a sufficient reduction for edge-nail holes.

Next, we will look at the effect of these edge-nail holes on bending strength to see if the same conclusion can be drawn.

Edge-Nail Orientation

The effect of edge-nail hole orientation (edge nails up or down in bending test) on strength and stiffness was also assessed. This analysis includes both data from this study as well as data from an earlier reclaimed lumber study

[1] By definition, equivalent holes per foot does not pertain to equivalent hole area, but rather equivalent diameters, as knots and holes are measured by the amount of board cross section that is displaced.

[2] Nails retrieved from the Washington 2 by 8s measured 1/8 in. by 3 in. long, comparable to a 10d box nail.

[3] Nails retrieved from the Washington 2 by 6s were non-standard and measured 3/32 in. by 1-1/8 in. long, similar in diameter to a 6d box nail, but the length of a 3d box nail.

Table 18—Equivalent holes allowed compared to actual

Grading rules (Standard No. 17)[a]				Equiv. holes/ft allowed ½-in. diameter rule[b]		Actual
Grade	Size	Max hole diameter (in.)	Equiv. holes over distance (ft)	1/8 in. diameter	3/16 in. diameter	average (holes/ft)[c]
No. 2	2 by 6	1.5	2	12.0	8.0	3.3 (4.4)
	2 by 8	2	2	16.0	10.7	2.5 (5.0)
	2 by 10	2.5	2	20.0	13.3	5.7 (8.3)
SS	2 by 6	1	4	4.0	2.7	3.3 (4.5)
	2 by 8	1.25	4	5.0	3.3	2.7 (5.5)
	2 by 10	1.25	4	5.0	3.3	5.8 (7.8)

[a] West Coast Lumber Inspection Bureau (2000).
[b] Displacement defined as ½ the diameter according to the edge spike knot analogy.
[c] Number in parentheses is absolute maximum number of holes per feet.

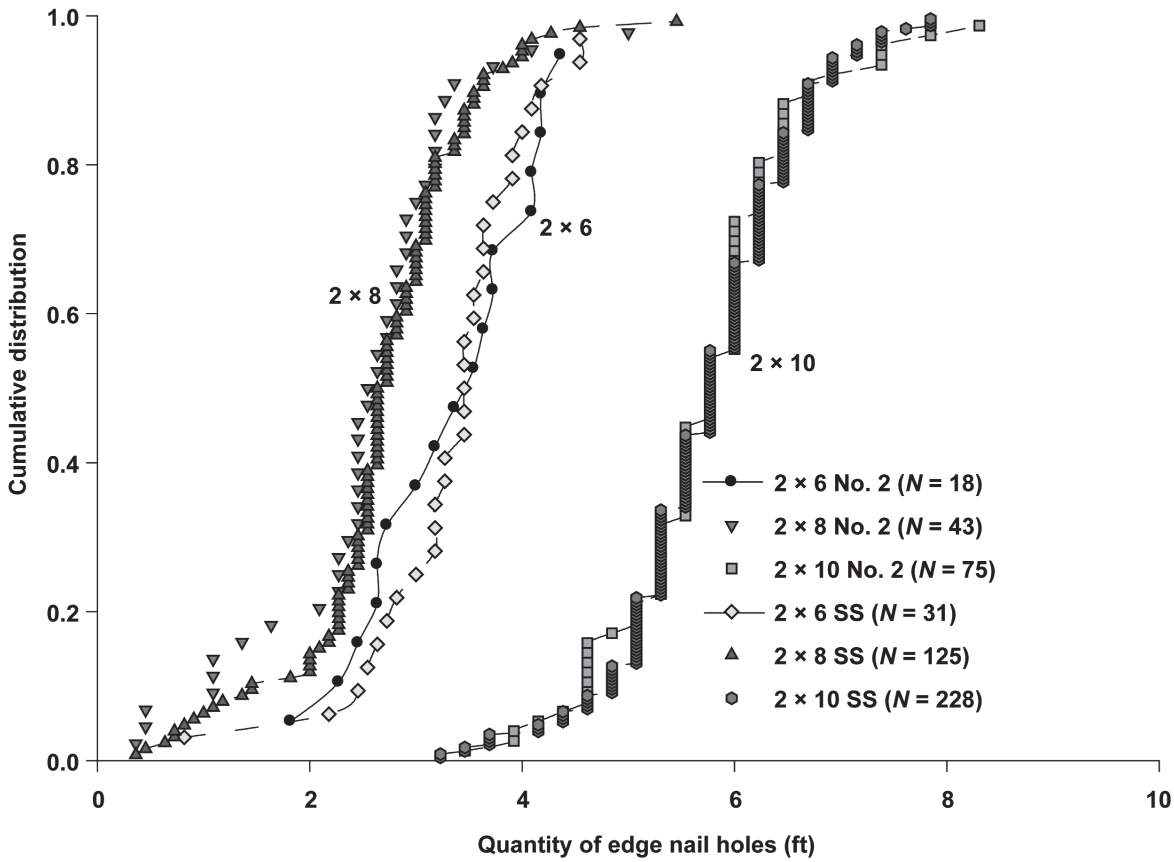

Figure 28—Cumulative distribution of edge-nail hole spacing by size–grade groups.

(Falk and others 1999c). In the earlier study, only edge-nail hole orientation was tracked, not specific nail-hole spacing.

Table 19 shows a statistical summary, including means and coefficient of variation for MOR. Also included are differences for the up (nail holes on the compression edge) and down (nail holes on the tension edge) means as well a simultaneous comparison of group MOR means at 95% confidence. Different MOR pairs are reported in the far right column.

In general, edge-nail holes on the tension side result in a lower board bending strength than when on the compression side. There was one exception to this, the 2 by 6 SS group, where MOR means were higher for the nail holes on the tension edge. This group had smaller nail holes and this likely was the reason for these contradictory results. The other group mean MORs have percentage reductions of 14.8 for 2 by 6 No. 2; 1.0 for 2 by 8 No. 2.; 18.4 for 11.6 2 by 8 SS; 12.4 for 2 by 10 No. 2.; and 2 by 10 SS. Only the 2 by 8 and

Table 19—Effect of edge-nail hole orientation on lumber modulus of rupture (MOR)

Size	Grade	Orientation[a]	N	Mean MOR ($\times 10^3$ lb/in^2)	Mean SG[b]	COV[c] MOR (%)	COV[c] SG dry (%)	U vs D difference[d] MOR (%)	U vs D difference[d] SG (%)	Different pairs[e]
2 by 6	No. 2[f] 5.28×10^3 lb/in^2[g]	U	40	5.62	0.488	42.1	11.3	14.8	– 3.9	None
		D	47	4.79	0.507	43.1	10.6	0.83	– 0.02	
		N	19	5.76	0.486	36.3	12.6			
	SS[h] 7.03×10^3 lb/in^2[g]	U	45	6.98	0.522	29.5	9.0	– 4.0	1.7	None
		D	44	7.26	0.513	31.9	12.0	– 0.28	0.01	
		N	6	5.43	0.536	43.3	15.0			
2 by 8	No. 2[i] 4.74×10^3 lb/in^2[g]	U	101	4.86	0.476	44.4	10.0	1.0	– 1.5	None
		D	104	4.81	0.483	40.4	10.7	0.05	– 0.01	
		N	7	4.76	0.509	54.9	14.0			
		B	22	4.31	0.472	42.5	9.6			
	SS[g] 6.11×10^3 lb/in^2[f]	U	80	6.57	0.495	31.5	12.7	18.4	1.2	D & N
		D	75	5.36	0.489	41.4	12.4	1.21	0.01	D & U
		N	4	8.59	0.487	16.9	23.3			
		B	3	7.64	0.579	19.2	20.3			
2 by 10	No. 2[j] 4.04×10^3 lb/in^2[g]	U	52	4.26	0.491	42.7	12.9	12.4	– 2.0	None
		D	39	3.73	0.501	41.7	13.0	0.53	– 0.01	
	SS[i] 5.65×10^3 lb/in^2[g]	U	144	6.02	0.512	32.3	11.1	11.6	– 1.6	D & U
		D	135	5.32	0.520	28.7	10.2	0.70	– 0.01	
		N	4	4.61	0.491	31.7	12.2			

[a] U is edge-nail holes tested up, D is edge-nail holes tested down, B is edge-nail holes present on both edges, and N is No edge-nail holes present.
[b] Specific gravity.
[c] Coefficient of variation is standard deviation/mean.
[d] Percentage difference is (U – D) / (U) and difference = U – D.
[e] For MOR, Tukey's studentized range (HSD) test at 95% or better confidence (SAS v8.2, GLM procedure).
[f] One board in this group had nail holes on both edges (not reported).
[g] As reported in Table 8, average group MOR for reclaimed lumber data set.
[h] Edge-nail hole information not available for one board in each of these groups.
[i] Edge-nail hole information not available for seven boards in each of these groups, one board contained holes on both edges (not reported).
[j] Edge-nail hole information not available for two boards in this group.

2 by 10 SS groups have a statistically significant difference at 95% confidence.

Recall that for the reclaimed lumber data set (Tables 8 and 9), the difference between the SS grade and the No. 2 grade MOR mean is 1.58×10^3 lb/in^2 on average for the three different sizes. Roughly speaking, this is approximately 800 lb/in^2 for each grade jump, No. 2 to No. 1, and No. 1 to SS. The effect of the edge nails on strength could justify a grade reduction as indicated by the 2 by 6 No. 2 group (830 lb/in^2 difference), 2 by 8 SS group (1,210 lb/in^2 difference), and perhaps the 2 by 10 SS group (700 lb/in^2). The differences between up (compression edge) and down (tension edge) in the 2 by 10 and 2 by 8 SS groups are consistent with the nail-hole spacing criteria discussed in the previous section. So, a one grade reduction might be justified for the presence of edge-nail holes (less than 1/8 in. diameter, no more than 2½ in. deep), or prescriptive rules could specify that edge-nail holes would be allowed only on the compression edge.

Edge-nail Location

It is possible that edge-nail hole characteristics (size and spacing) are different for different geographical locations because of different construction techniques, environmental conditions, or usage. To investigate this, an additional analysis was performed. In this analysis, only SS grades were analyzed because of the confounding of MOR by the greater number (and size) of natural defects in the No. 2 groups. The analysis focused on 2 by 8s and 2 by 10s, the sizes that showed statistically significant differences in MOR means between edge-nail holes tested up compared with down (Table 20).

Table 20—Edge-nail hole orientation for Select Structural (SS) grade by size and location

				Mean				COV[c]		U vs D difference[d]	
Location	Size	Orientation[a]	N	MOR ($\times10^3$ lb/in^2)	SG[b]	MOE ($\times10^3$ lb/in^2)	Nail spacing (holes/ft)	MOR (%)	SG (%)	MOR (%)	SG (%)
Washington	2 by 6	U	16	6.41	0.508	2.57	3.26	26	6	– 6.4	2.8
		D	15	6.82	0.493	2.41	3.42	32	11	– 0.41	0.014
	2 by 8	U	63	6.15	0.485	2.25	2.67	31	13	15.3	0.6
		D	62	5.21	0.482	2.26	2.70	43	12	0.94	0.003
Oakland	2 by 10	U	86	6.35	0.527	2.79	5.95	30	10	14.4	– 0.1
		D	90	5.44	0.528	2.77	5.88	26	10	0.91	0.000
Minnesota	2 by 10	U	28	5.73	0.492	1.98	5.25	28	12	10.5	– 2.8
		D	24	5.13	0.506	2.03	5.16	35	11	0.60	– 0.014

[a] U is edge nail holes on compression edge (up), D is edge nail holes on tension edge (down).
[b] Specific gravity.
[c] Coefficient of variation is standard deviation/mean.
[d] Percentage difference is (U – D) / (U) and difference is U – D.

Mean MOR, SG, MOE, and nail-hole spacing for the different size–location–orientation groups are shown in Table 20. Also listed are differences in MOR and SG for the up compared with down edge-nail hole orientation.

Results indicate that the only group that does not exhibit a substantial difference in MOR was the Washington 2 by 6s. This is consistent with the combined findings for the 2 by 6 SS group in Table 20, and is likely explained because the holes were smaller for this group.

The Washington 2 by 8 group showed a significant increase in mean MOR when placing the edge-nail holes on the compression edge, 940 lb/in.^{2} (Table 20). The cumulative distribution curves for MOR values of the up (compression edge) and down (tension edge) groups are shown in Figure 29. The tension-edge curve is shifted left (lower MOR) at the low end of the distribution until the very high end where the curves meet. This would imply that both the up and down groups contained some stronger boards in which nail holes did not affect MOR. Also note that a greater shift appears in the curves near the middle of the distribution as compared with the lower end. This could imply that nail-hole orientation has less of an effect on boards that contain other MOR-lowering defects.

For the same group, 2 by 8 Washington, mean MOE, SG, and nail-hole spacing are all very close for the up (compression edge) and down (tension edge) orientations (Table 20), which would imply negligible to no effects of these other variables on MOR mean. Of course, we would expect MOE to be close for the two groups, as this was the variable used to sort the two groups initially.

Cumulative distributions of SG and MOE for the up and down groups are plotted in Figures 30 and 31, respectively. The SG curves are not the same shape, with the down curve shifted leftward (lower SG) at the extremes, and rightward (higher SG) near the center of the distribution. The curves do appear to average out throughout the rest of the distribution. However, recall that SG is not strong as a predictor of MOR as MOE.

The Oakland 2 by 10 SS grade group exhibited very similar results. Mean MOR increased 910 lb/in^2 or around 14% for the group of boards tested with the nail holes on the compression edge (Table 20 and Figure 32). As with the Washington 2 by 8s, mean SG, MOE, and nail-hole spacing were all very similar for the up and down groups (Figs 33, 34).

Minnesota 2 by 10s were the last SS grade group examined for edge-nail-hole orientation. This group also showed a shift in mean MOR of 600 lb/in^2 (Table 20, Fig. 35), though not as much as the Oakland 2 by 10 SS group (910 lb/in^2). Specific gravity or MOE have likely lessened the difference in MOR mean between up and down, as mean SG and MOE are larger for the down group (Table 20). This shift in SG and MOE can be seen in the upper portion of the cumulative distributions (Figs 36 and 37). Mean holes spacing, on the other hand, does compare well (Table 20).

The analysis was taken one step further to see if MOR was affected as greatly when nail-hole spacing was reduced or increased. Scatter plots were constructed with linear regression curves of MOR compared with nail-hole spacing for the 2 by 8 Washington SS group, 2 by 10 Oakland SS group, and the 2 by 10 Minnesota SS group (Figs 38, 39, and 40, respectively). Although correlation coefficients are low, the Washington and Oakland groups do exhibit a downward trend in MOR as nail-hole spacing decreases, greater for the Washington group (Figs 38 and 39). This trend was not seen in the Minnesota group (Fig. 40), which could also explain why the MOR means did not show a statistically significant difference.

Face Nails

Much of the lumber contained consistent face-nail-hole patterns (Code NF, Table 17, especially the 2 by 10s, which

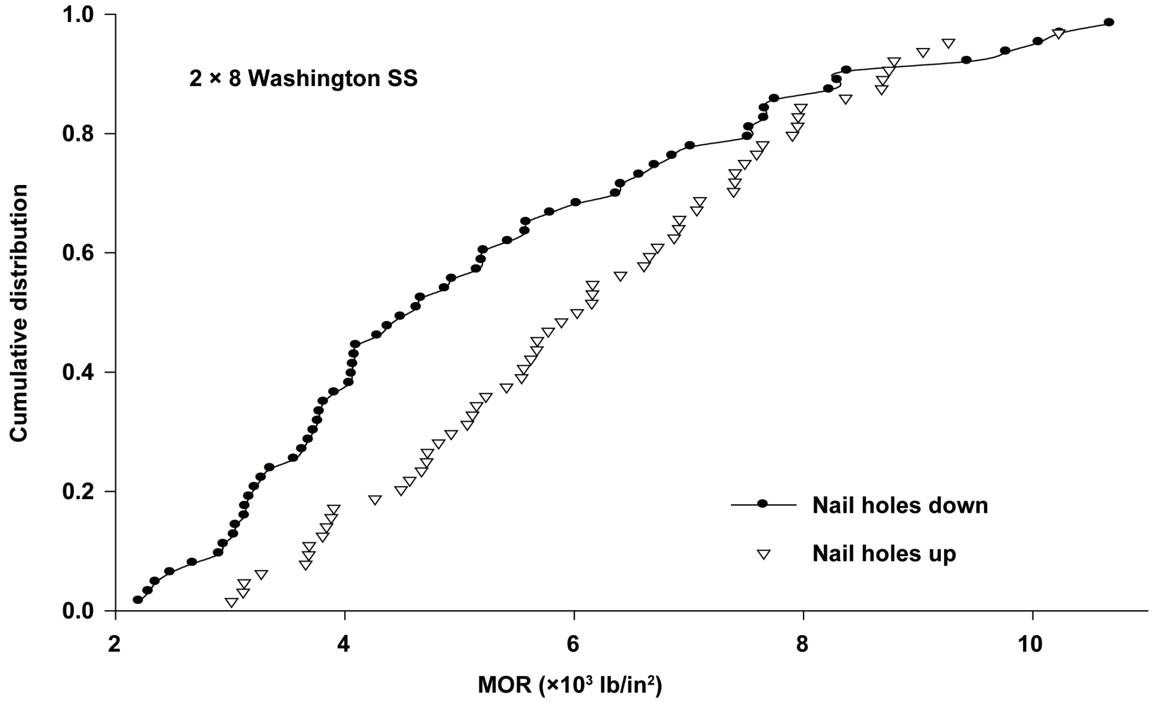

Figure 29—Cumulative distribution of modulus of rupture (MOR) for up and down nail hole orientation for Washington 2 by 8 SS group.

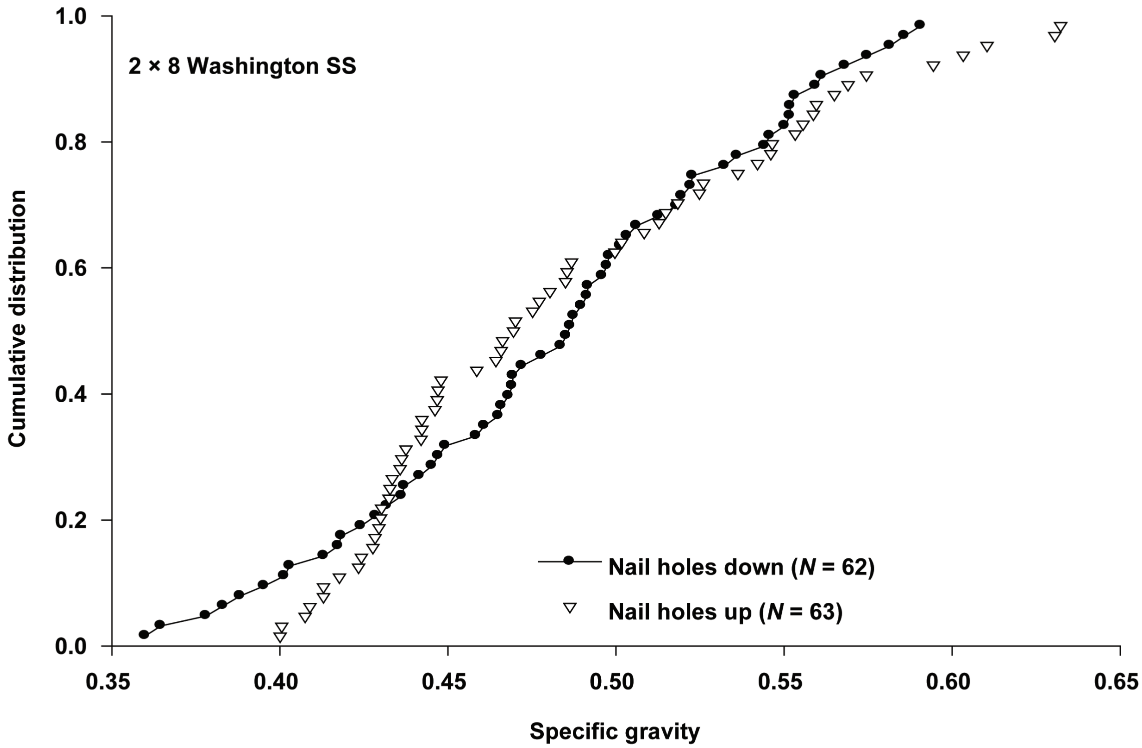

Figure 30—Cumulative distribution of specific gravity (SG) for up and down nail hole orientation for Washington 2 by 8 SS group.

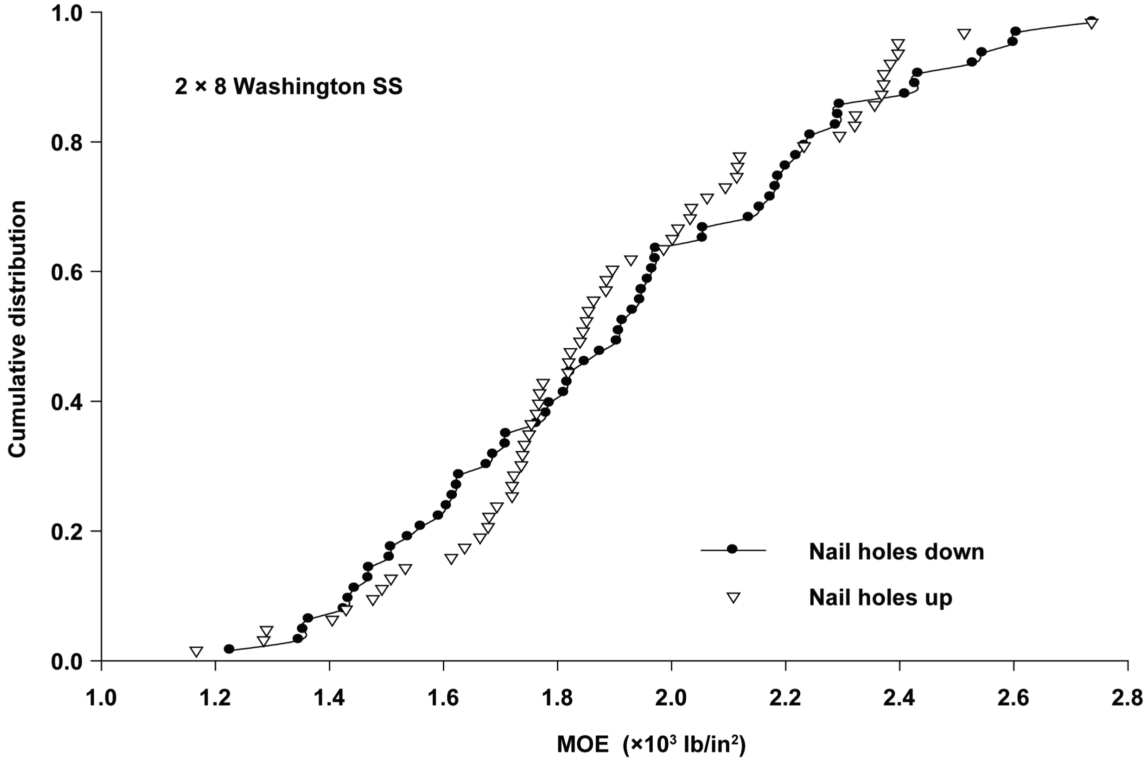

Figure 31—Cumulative distribution of modulus of elasticity (MOE) for up and down nail hole orientation for Washington 2 by 8 SS group.

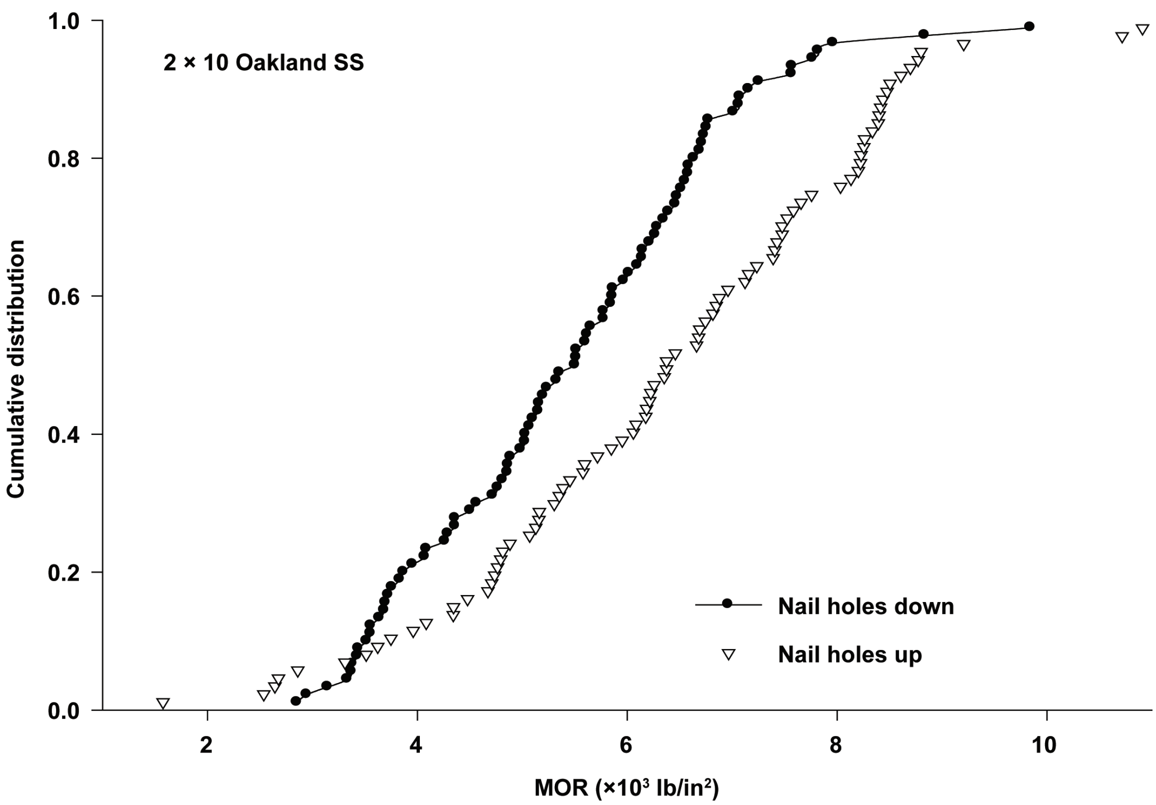

Figure 32—Cumulative distribution of modulus of rupture (MOR) for up and down nail hole orientation for Oakland 2 by 10 SS group.

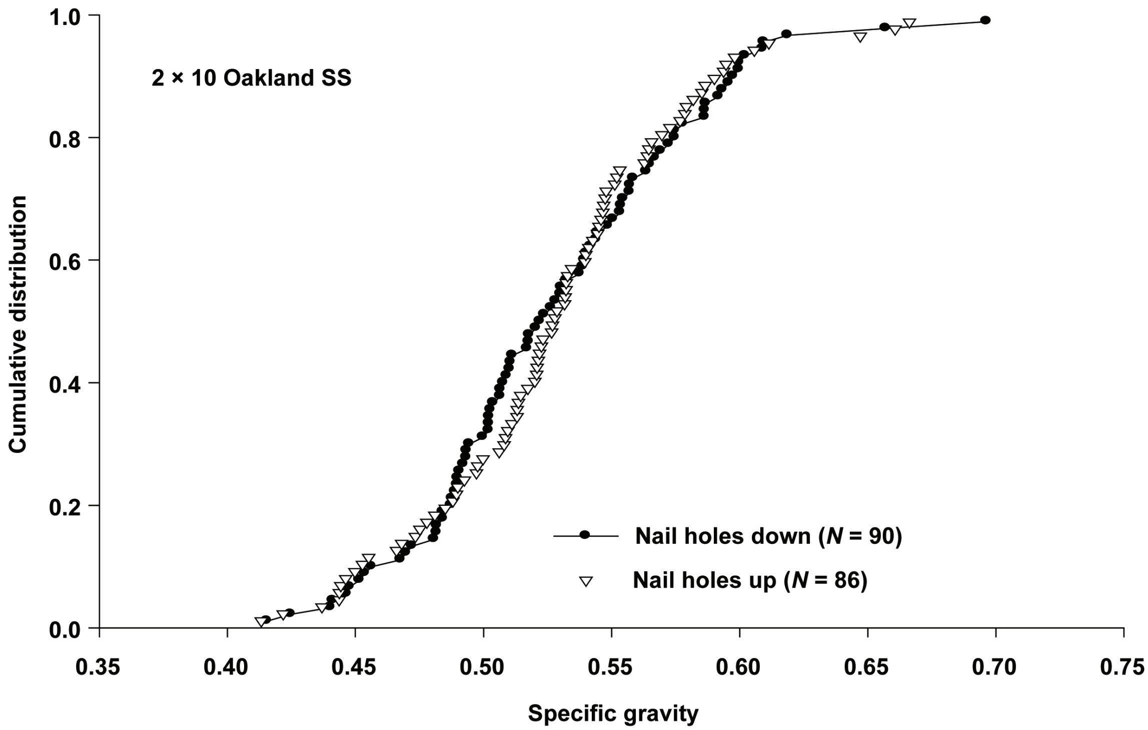

Figure 33—Cumulative distribution of specific gravity (SG) for up and down nail hole orientation for Oakland 2 by 10 SS group.

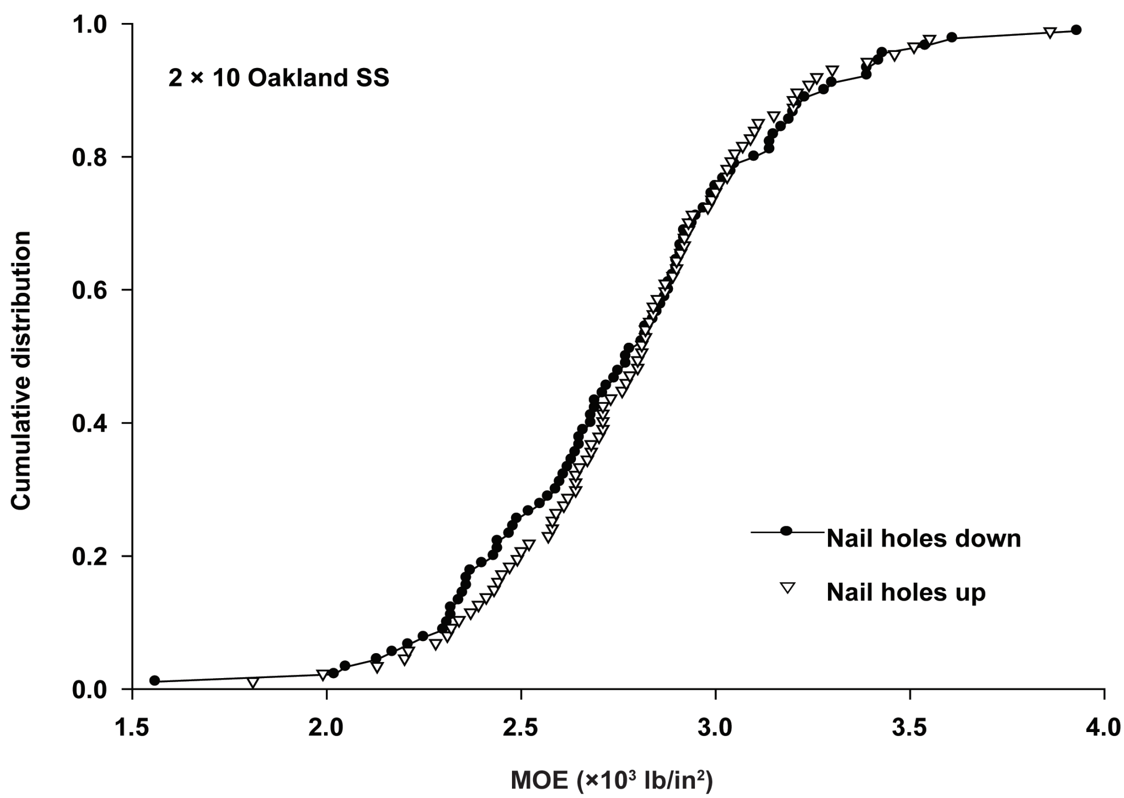

Figure 34—Cumulative distribution of modulus of elasticity (MOE) for up and down nail hole orientation for Oakland 2 by 10 SS group.

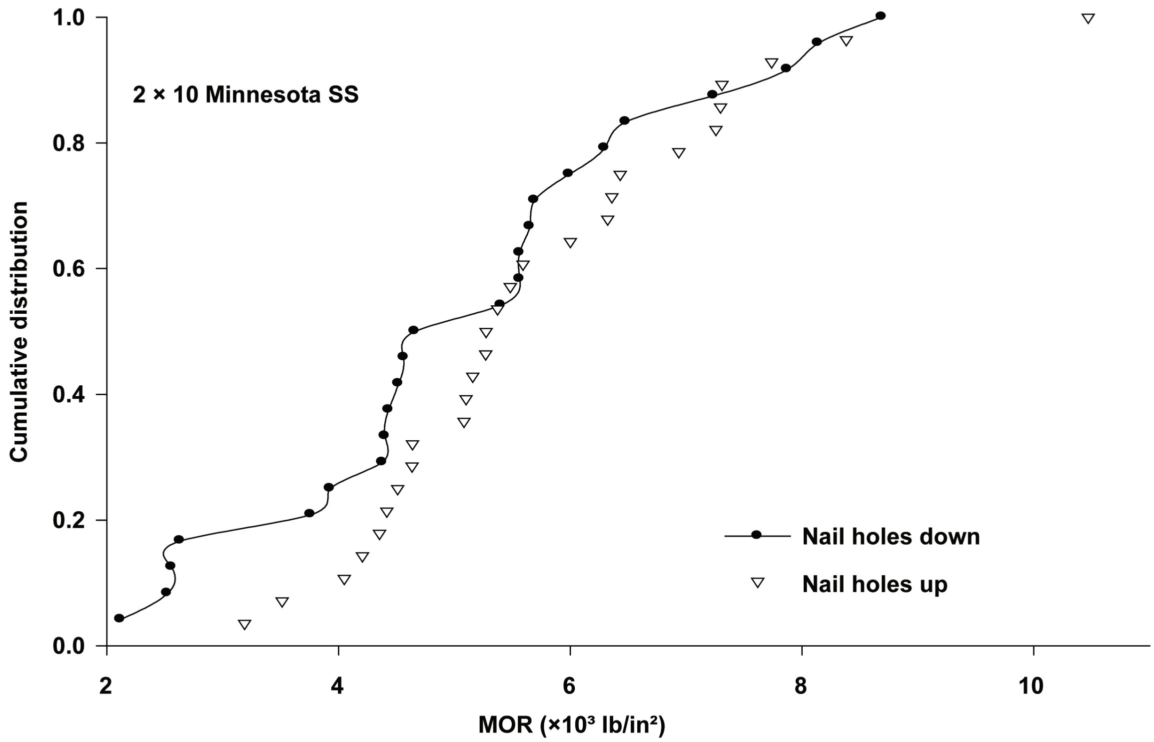

Figure 35—Cumulative distribution of modulus of rupture (MOR) for up and down nail hole orientation for Minnesota 2 by 10 SS group.

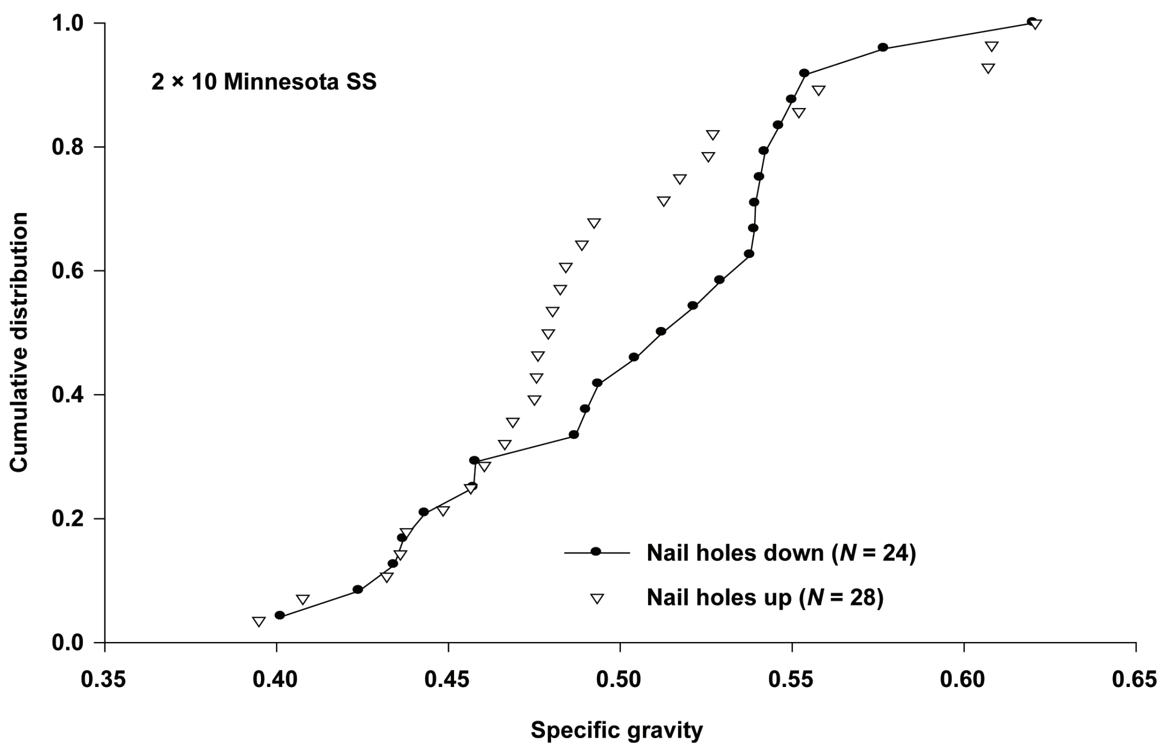

Figure 36—Cumulative distribution of specific gravity (SG) for up and down nail hole orientation for Minnesota 2 by 10 SS group.

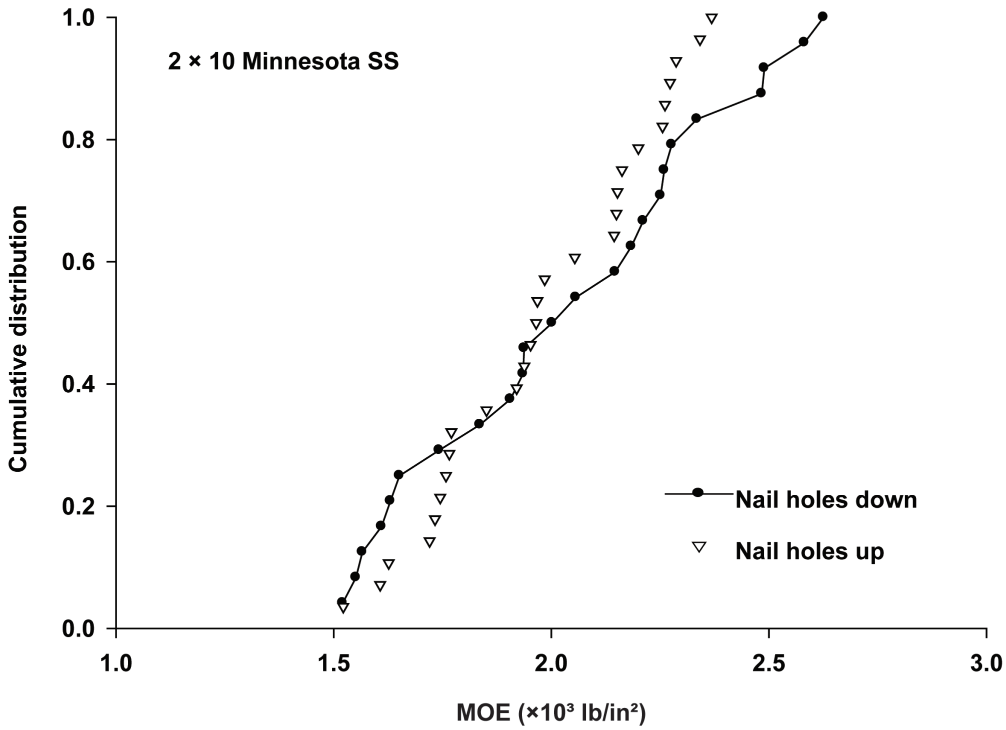

Figure 37—Modulus of rupture (MOR) compared with up and down nail hole orientation for Minnesota 2 by 10 SS group.

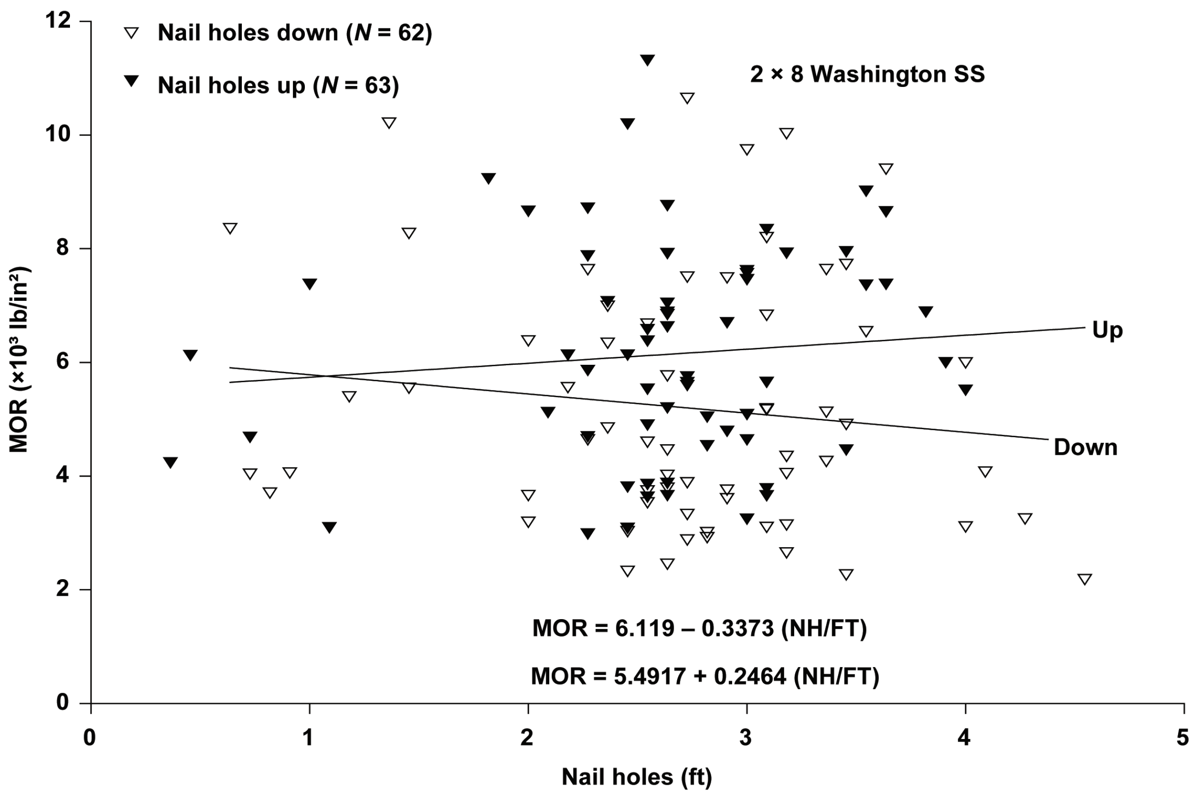

Figure 38—Modulus of rupture (MOR) compared with up and down nail hole orientation for Washington 2 by 8 SS group. NH/FT is nail holes per foot.

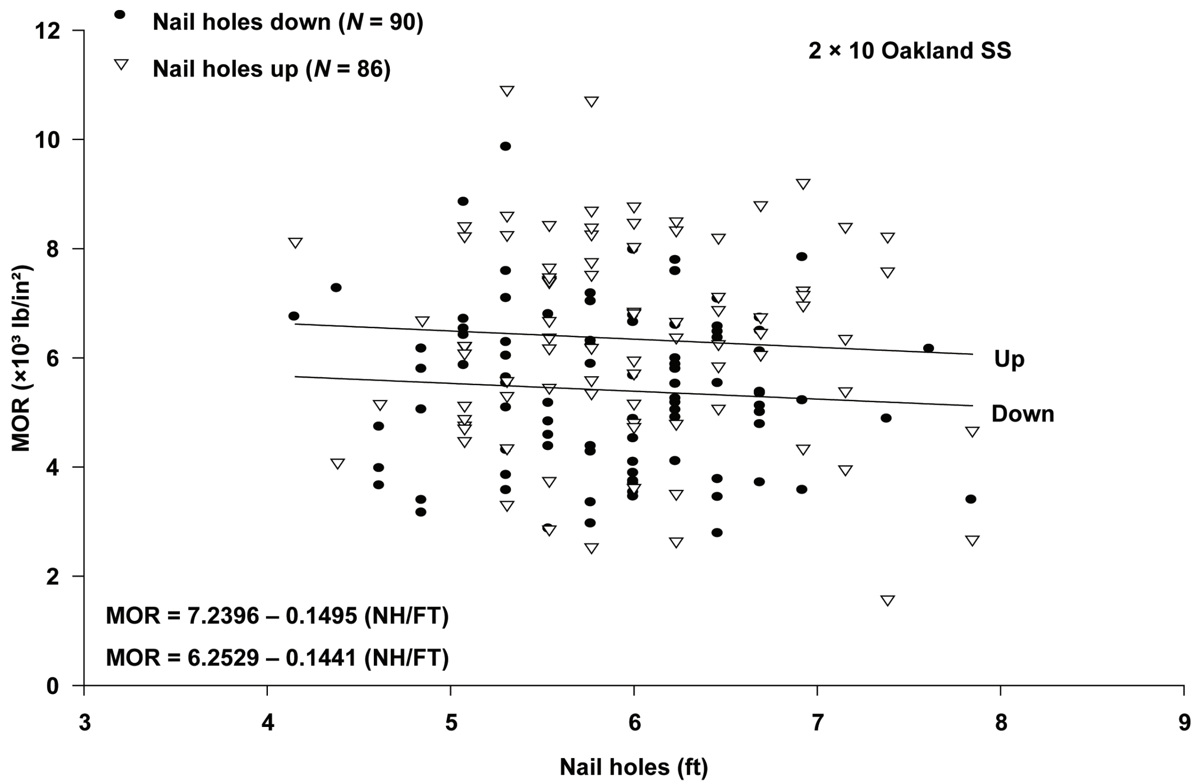

Figure 39—Modulus of rupture (MOR) compared with up and down nail hole orientations for Oakland 2 by 10 SS group. NH/FT is nail holes per foot.

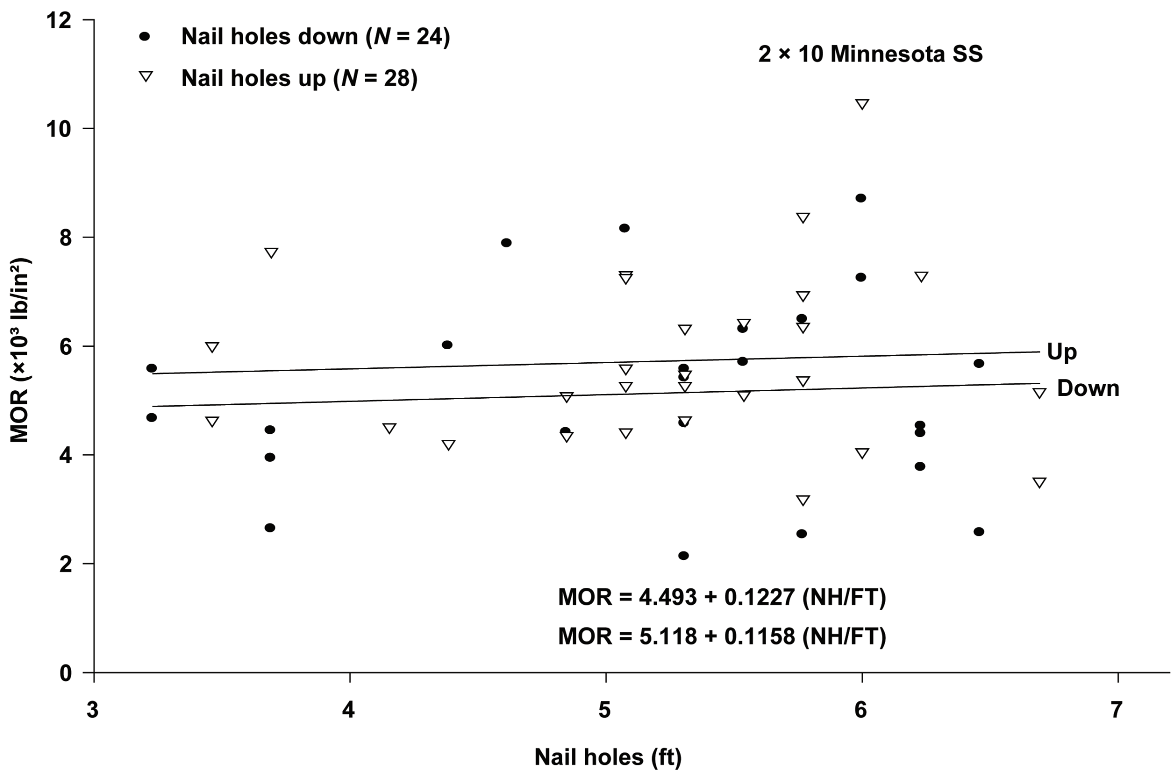

Figure 40—Modulus of rupture (MOR) compared with up and down nail hole orientation for Minnesota 2 by 10 SS group. NH/FT is nail holes per foot.

contained nail holes from the prior attachment of cross bridging typically used to provide lateral stability and load distribution to the bending members (Fig. 41). These holes were typically found on the face, near both edges of the board.

Pairs of face holes from the prior attachment of wire-type hangers commonly used to support mechanical piping were also found (Fig. 42). These holes were very near the center of the face, and stains from the hanger could be seen. These holes often times were caused through splits from wedging along the grain (Fig. 43). If these holes were near the end of a board, horizontal shear failures were more likely to occur (Fig. 43). The lower piece of the failed board in Figure 43 has been turned to view the grain face of the split. Note the discoloration and additional staining at the fastener holes, which indicates the presence of a substantial through split prior to testing.

Another type of repetitive face-nail hole was found in the Oakland 2 by 6 group of lumber. These boards were once wall studs that had blocking between each stud near the mid-height of the wall. The blocking was oriented such that the face of the blocking was at the outside face of the stud, with the 2-in. nominal dimension parallel to the 6-in. nominal dimension of the wall stud. This blocking created face-nail holes within 1-1/2 in. of the edge of the board (Fig. 44). This damage was so consistent that an experiment was designed exactly like the edge-nail holes, to see if placing this damage up or down during testing had an effect on mechanical properties.

Table 21 summarizes the result of this experiment, showing mean properties and coefficients of variation (COV) for MOR, MOE, and SG for the up and down groups of boards. No statistical significance was found between the two groups. In fact, average MOR for the down group was approximately 8% larger for the group of boards tested with the face-nail holes down.

These results illustrate that a nail hole, or tip of the crack, needs to be located at the region of highest stress to have an effect on fracture and hence bending strength. In other words, cracks have to form on the tension edge, where failure begins, for these nail holes to come into play. Also, these nail holes extended from one face directly to the other. This meant that an unaffected piece of wood still existed, below the holes, at the tension edge, providing an uninterrupted route for the greatest tension stress path. This is consistent with the simulated hole study by Falk and others (2003). In a few cases, the holes did extend from one face to the tension edge of the board (toenail holes, Code NT, Table 17), potentially initiating a split at the tension edge and causing the board to fail (Fig. 45).

Table 21—Property comparison for 2 by 6 Oakland Select Structural (SS). Effect of face-nail hole orientation during testing

	Up			Down			Difference (%)[a]	
Property	*N*	Mean	COV (%)[b]	*N*	Mean	COV (%)[b]	Mean	COV (%)[b]
MOR ($\times 10^3$ lb/in^2)	25	7.02	29.5	22	7.56	32.2	– 7.6	– 9.3
MOE ($\times 10^6$ lb/in^2)	25	2.14	15.6	22	2.28	18.3	– 6.3	– 17.4
Specific gravity	25	0.531	9.6	22	0.533	12.3	– 0.4	– 28.1

[a] Percentage difference is (up – down) / (up).
[b] Coefficient of variation is standard deviation/mean.

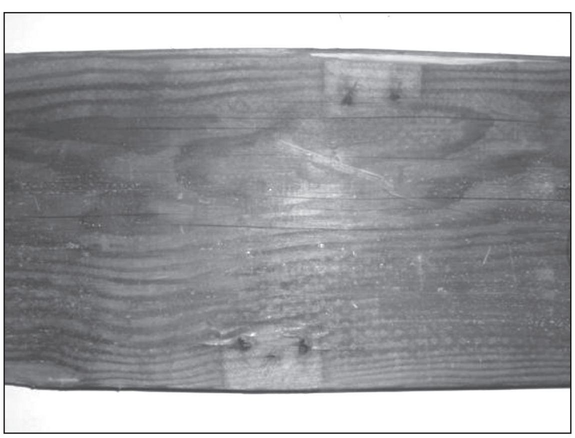

Figure 41—Example of face nail holes in 2 by 10s from prior attachment of cross-bridging.

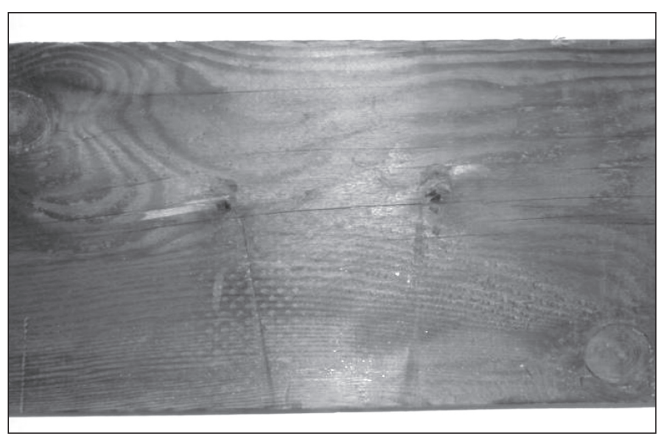

Figure 42—Example of face nail holes in 2 by 10s from prior attachment of wire-type mechanical hangers.

Figure 43—Example of failed 2 by 10 board where through splits from face nail holes caused horizontal shear failure.

Figure 44—Example of face-nail holes in Oakland 2 by 6 wall studs from prior attachment of blocking.

Figure 45—Example of toenail holes in an Oakland 2 by 6, potentially initiating a failure split.

Face Checks

Through splitting (Table 17) was a damage category with a related widespread phenomena—face checking. Face checking is typical in nearly every reclaimed lumber piece; however, the severity varies. To investigate the effect of face checks on lumber strength, boards were sorted based on a general ranking (1, 2, or 3) of face-checking severity: 1 was none to few, 2 was medium, and 3 was more severe. Face checking is not limited in existing grading rules for structural joists and planks. Figures 46 and 47 indicate medium checking and severe checking, respectively.

Only SS grade boards were examined, to avoid additional confounding effects for boards with known natural defects. The groups were also sorted by edge-nail hole orientation, because statistically significant effects were found for this variable as indicated in previous sections. Table 22 summarizes means and COV for MOR, MOE, and SG for the three different checking levels.

Results indicate that checking levels do not affect MOE or SG. These variables were included to verify that they do not have an affect on MOR. Although statistically significant differences are not indicated, mean trends are interesting. For four out of the six groups, mean SG increases as the level of checking increases. Modulus of rupture does not show any consistent trends, although one group, Washington 2 by 8 D, had the highest mean in the lowest check-level group.

Overall, there were no conclusive results from this analysis. It is therefore reasonable to assume that a limit on face checking specifically for reclaimed 2-by lumber may not be warranted. Note however, that Falk (1999b) found that severe heart checks in timbers reduced MOR by about 15%.

Damage Categories

As indicated in Table 17, three damage categories were established; nail-hole damage, through-splitting damage (a split completely through the board from face to face), and other mechanical damage. In the previous section, we looked at the effect of a specific damage type (for example, edge nails, face checks) on properties. In this section, we will look at the effect of these damage categories on properties. In essence, we are combining like damage into separate categories for comparison. For each of these categories, data were sorted by size, grade, and whether or not damage was involved in failure.

Nail-Hole Damage

Table 23 shows the results for the nail-hole damage category. Note that percentage of differences are shown for the MOR mean, as well as the MOR mean adjusted for the percentage difference in MOE mean, in order to approximately capture the effect of stiffness (MOE) on MOR. Looking at the adjusted percentage differences, all the No. 2 boards with nails involved in the failure were stronger than the No. 2 boards where there was no damage involved with the failure. This might be explained by the fact that the board didn't necessarily fail at the defect that placed it into the No. 2 grade. For the SS grades, 2 by 8 and 2 by 10 adjusted MOR percentage differences show that mean MOR is slightly lower (by 2.7% and 1.5%, respectively) for the boards with nails involved with failure than those boards where nails were not involved in the failure. For the 2 by 6 SS group, the opposite is shown. So, no clear trend is indicated for the effects of this category of nail-hole damage on MOR.

Table 22—Property mean comparisons by face-check level for SS grade

Size	Location	Orient[b]	Property (units)	Check level 1 *N*	Check level 1 Mean	Check level 1 COV (%)[c]	Check level 2 *N*	Check level 2 Mean	Check level 2 COV (%)[c]	Check level 3 *N*	Check level 3 Mean	Check level 3 COV (%)[c]	Difference[a] 1 to 2 (%)[d]	Difference[a] 2 to 3 (%)[d]
2 by 8	Washington	D	MOR ($\times 10^3$ lb/in^2)	5	6.00	33	54	5.14	44	3	5.18	43	14	– 1
			MOE ($\times 10^6$ lb/in^2)	5	1.78	21	54	1.91	19	3	2.19	23	– 7	– 15
			Specific gravity	5	0.48	16	54	0.482	12	3	0.48	12	– 1	– 1
		U	MOR ($\times 10^3$ lb/in^2)	2	5.14	24	55	6.08	32	6	6.89	22	– 18	– 13
			MOE ($\times 10^6$ lb/in^2)	2	1.73	21	55	1.88	17	6	2.13	15	– 9	– 13
			Specific gravity	2	0.43	5	55	0.485	13	6	0.50	10	– 12	– 4
2 by 10	Oakland	D	MOR ($\times 10^3$ lb/in^2)	11	5.40	27	12	4.85	31	10	5.42	28	10	– 12
			MOE ($\times 10^6$ lb/in^2)	11	2.03	24	12	2.11	16	10	2.35	13	– 4	– 12
			Specific gravity	11	0.52	8	12	0.531	8	10	0.53	8	– 2	– 1
		U	MOR ($\times 10^3$ lb/in^2)	6	5.85	22	12	6.94	32	12	6.42	30	– 19	8
			MOE ($\times 10^6$ lb/in^2)	6	2.13	6	12	2.41	20	12	2.27	17	– 13	6
			Specific gravity	6	0.52	8	12	0.544	11	12	0.54	5	– 4	1
	Minnesota	D	MOR ($\times 10^3$ lb/in^2)	6	5.22	46	14	5.10	34	4	5.93	27	2	– 16
			MOE ($\times 10^6$ lb/in^2)	6	2.10	19	14	1.97	17	4	2.31	11	6	– 17
			Specific gravity	6	0.48	11	14	0.495	12	4	0.55	4	– 2	– 11
		U	MOR ($\times 10^3$ lb/in^2)	6	5.45	22	15	6.13	27	7	5.10	35	– 12	17
			MOE ($\times 10^6$ lb/in^2)	6	1.85	12	15	2.07	9	7	1.90	16	– 12	8
			Specific gravity	6	0.46	4	15	0.502	12	7	0.49	15	– 8	2

[a] Difference is (level 1 – level 2) / (level 1) or difference (%) = (level 2 – level 3) / (level 2).
[b] Orientation of regular edge nail holes during testing: D, down; U, up.
[c] Coefficient of variation = standard deviation/mean, also shaded cells indicate COV is higher than overall reclaimed lumber average (Table 3).
[d] Shaded cells indicate property mean decreases with the increase in split level.

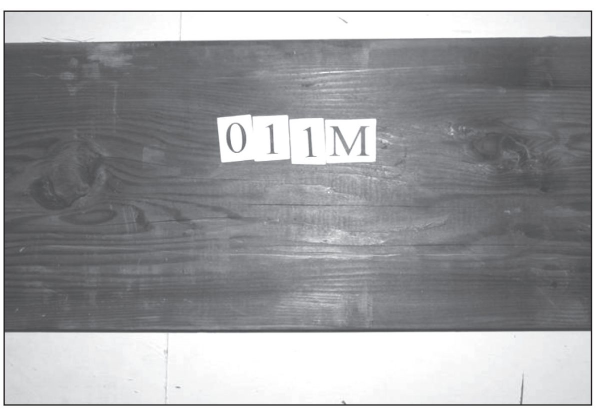

Figure 46—Example of medium face checks.

Figure 47—Example of severe face checks.

Table 23—Property comparisons for nail-hole damage category

Size	Grade	Property	No defect[a]		Defect[b]		Difference (%)		With defect (%)[c]
			N	Mean	*N*	Mean	Mean[d]	MOR[e]	*N*
2 by 6	No. 2	MOR ($\times 10^3$ lb/in^2)	82	5.08	12	6.12	20.5	18.0	14.6
		MOE ($\times 10^6$ lb/in^2)	80	1.75	12	1.80	2.5		15.0
		Specific gravity	82	0.49	12	0.48	– 2.0		14.6
	SS	MOR ($\times 10^3$ lb/in^2)	70	7.02	11	8.18	16.5	6.4	15.7
		MOE ($\times 10^6$ lb/in^2)	68	2.07	11	2.28	10.2		16.2
		Specific gravity	70	0.51	11	0.55	8.0		15.7
2 by 8	No. 2	MOR ($\times 10^3$ lb/in^2)	83	4.51	17	5.21	15.5	2.2	20.5
		MOE ($\times 10^6$ lb/in^2)	32	1.63	9	1.85	13.4		28.1
		Specific gravity	83	0.48	17	0.51	6.2		20.5
	SS	MOR ($\times 10^3$ lb/in^2)	125	6.14	30	6.10	– 0.6	– 2.7	24.0
		MOE ($\times 10^6$ lb/in^2)	96	1.89	24	1.93	2.1		25.0
		Specific gravity	125	0.49	30	0.51	4.5		24.0
2 by 10	No. 2	MOR ($\times 10^3$ lb/in^2)	57	3.78	10	5.18	37.1	26.3	17.5
		MOE ($\times 10^6$ lb/in^2)	57	1.75	10	1.94	10.8		17.5
		Specific gravity	57	0.50	10	0.52	2.9		17.5
	SS	MOR ($\times 10^3$ lb/in^2)	151	5.81	54	5.77	– 0.6	– 1.5	35.8
		MOE ($\times 10^6$ lb/in^2)	151	2.16	54	2.18	0.9		35.8
		Specific gravity	151	0.51	54	0.52	2.2		35.8
All		MOR	568		134				23.6
		MOE	484		120				24.8

[a] No apparent damage defect involved in failure.
[b] Nail hole defect involved in failure.
[c] Percentage of pieces with defects involved in failure out of all pieces within size grade group.
[d] Percentage difference of mean MOR is (defect – no defect) / (no defect).
[e] Percentage difference of mean MOR adjusted for MOE is $[(MOR_{Defect} - MOR_{No\ Defect}) / MOR_{No\ Defect}] - [(MOE_{Defect} - MOE_{No\ Defect}) / MOE_{No\ Defect}]$

Through-Splitting Damage

The through-splitting damage category showed more consistent and anticipated results (Table 24). When adjusting the MOR mean for MOE, all the size and grade groups had lower MORs when through-splitting damage was involved in failure. The difference in strength ranged from approximately 9% for the 2 by 10 SS to approximately 27% for the 2 by 6 No. 2. The trends are very consistent for each grade between the different sizes, with the difference increasing as the size decreases. For the No. 2 grade, differences are 14.4%, 17.6%, and 26.7% for the 2 by 10, 2 by 8, and 2 by 6 sizes, respectively. For SS grade, differences are 8.9%, 20.0%, and 23.7% for the 2 by 10, 2 by 8, and 2 by 6 sizes, respectively. An explanation might be that for the same size and type of split, the defect becomes a larger percentage of the section as the size of the board decreases, hence having a greater decrease on MOR. Interestingly the SS grades for two of the three sizes show less of a difference, likely because the severity of splitting was not as great as for the No. 2 grade.

Other Mechanical Damage

Table 25 summarizes the same type of results for the other mechanical damage category. Recall that this category includes damage from mechanical gouging, man-made drilled holes, and cuts and notches. After adjusting for MOE, all the No. 2 grade MORs are greater for boards failing at damage. This likely carries the same explanation given for the nail-hole damage category. The No. 2 boards did not fail by the grade-determining defect, and the other mechanical defect is likely not as detrimental to strength as the grade-determining defect. All the SS grade groups show a decrease in MOR, according to the MOE adjustment, with

Table 24—Point-damage mean property comparisons for the through-splitting damage category

Size	Grade	Property	No defect[a]		Defect[b]		Difference (%)		With defect (%)[c]
			N	Mean	*N*	Mean	Mean (%)[d]	MOE (%)[e]	*N*
2 by 6	No. 2	MOR ($\times 10^3$ lb/in^2)	82	5.08	6	4.95	– 2.5	– 26.0	7.3
		MOE ($\times 10^6$ lb/in^2)	80	1.75	6	2.18	24.2		7.5
		Specific gravity	82	0.49	6	0.57	16.5		7.3
	SS	MOR ($\times 10^3$ lb/in^2)	70	7.02	12	6.44	– 8.3	– 23.7	17.1
		MOE ($\times 10^6$ lb/in^2)	68	2.07	12	2.39	15.4		17.6
		Specific gravity	70	0.51	12	0.56	9.4		17.1
2 by 8	No. 2	MOR ($\times 10^3$ lb/in^2)	83	4.51	5	5.35	18.6	– 17.6	6.0
		MOE ($\times 10^6$ lb/in^2)	32	1.63	1	2.22	36.1		3.1
		Specific gravity	83	0.48	5	0.48	1.0		6.0
	SS	MOR ($\times 10^3$ lb/in^2)	125	6.14	5	5.57	– 9.2	– 20.0	4.0
		MOE ($\times 10^6$ lb/in^2)	96	1.89	4	2.09	10.7		4.2
		Specific gravity	125	0.49	5	0.56	15.1		4.0
2 by 10	No. 2	MOR ($\times 10^3$ lb/in^2)	57	3.78	4	3.50	– 7.4	– 14.4	7.0
		MOE ($\times 10^6$ lb/in^2)	57	1.75	4	1.88	7.0		7.0
		Specific gravity	57	0.50	4	0.49	– 2.6		7.0
	SS	MOR ($\times 10^3$ lb/in^2)	151	5.81	45	5.55	– 4.4	– 8.9	29.8
		MOE ($\times 10^6$ lb/in^2)	151	2.16	45	2.26	4.5		29.8
		Specific gravity	151	0.51	45	0.53	4.3		29.8
All		MOR	568		77				13.6
		MOE	484		72				14.9

[a] No apparent damage defect involved in failure.
[b] Through-splitting defect involved in failure.
[c] Percentage of pieces with nail hole defects involved in failure out of all pieces within size grade group.
[d] Percentage difference of mean MOR is (defect – no defect) / (no defect).
[e] Percentage difference of mean MOR adjusted for MOE is [(MOR defect – MOR no defect) / MOR no defect] – [(MOE defect – MOE no defect) / MOE no defect].

the other mechanical damage involved, ranging from 14.5% for the 2 by 6 group to 25.4% for the 2 by 10 group. This trend is opposite to what was shown for the through-splitting damage group.

The magnitude or size of the defect was not evaluated for all these analyses. Rather, we were only able to document if the damage was involved in the failure, although not necessarily initiating it. Also, involvement in failure carries a fairly broad definition. Simply examining a failed board makes it difficult to make that exact determination, though in many cases it may be deduced with relative certainty. Also, the sample sizes in this analysis were fairly small, and given the inherent variability of wood, this makes most conclusions gathered from this analysis rather weak. Last, other effects known to have statistically significant effects on MOR, such as location, edge-nail hole orientation, and damage downgrading, could not be included in the sorting as the sample sizes would have become too small.

Full-Size Lumber Failure Types

Up to this point, we have focused on comparing lumber failures caused by damage to "the rest of the population" of lumber. In this section, we will look more specifically at how these damage failures compare to the more typical types of lumber failures (e.g, wood tension, knots, SOG, see Table 2). Tension-type failures are broken down into four categories according to the failure defect (clear wood, knot, damage, and slope of grain).

No. 2 Grade

First, we will look at the No. 2 grade, then SS. The frequency of failure types for all sizes of the No. 2 grade are summarized in Table 26. Note that three of the tension failure types (Table 27, code 2, 3, and 4) match specific GDDs such as knots, damage, and slope of grain (Table 28, code 3, 5, and 7). Comparing the frequencies for all sizes, there were about 13% more knot failures, approximately 26% fewer

Table 25—Point damage mean property comparisons for other mechanical damage category

Size	Grade	Property	No defect[a]		Defect[b]		Difference (%)		With defect (%)[c]
			N	Mean	*N*	Mean	Mean (%)[d]	MOR (%)[e]	*N*
2 by 6	No. 2	MOR ($\times 10^3$ lb/in^2)	82	5.08	7	6.36	25.2	20.8	8.5
		MOE ($\times 10^6$ lb/in^2)	80	1.75	5	1.83	4.4		6.3
		Specific gravity	82	0.49	7	0.49	– 0.7		8.5
	SS	MOR ($\times 10^3$ lb/in^2)	70	7.02	3	5.30	– 24.5	– 14.5	4.3
		MOE ($\times 10^6$ lb/in^2)	68	2.07	3	1.86	– 10.0		4.4
		Specific gravity	70	0.51	3	0.46	– 9.0		4.3
2 by 8	No. 2	MOR ($\times 10^3$ lb/in^2)	83	4.51	2	4.55	0.9	0.3	2.4
		MOE ($\times 10^6$ lb/in^2)	32	1.63	1	1.64	0.6		3.1
		Specific gravity	83	0.48	2	0.49	1.7		2.4
	SS	MOR ($\times 10^3$ lb/in^2)	125	6.14	1	5.21	– 15.0	– 19.4	0.8
		MOE ($\times 10^6$ lb/in^2)	96	1.89	1	1.97	4.4		1.0
		Specific gravity	125	0.49	1	0.51	3.9		0.8
2 by 10	No. 2	MOR ($\times 10^3$ lb/in^2)	57	3.78	7	4.30	13.8	12.4	12.3
		MOE ($\times 10^6$ lb/in^2)	57	1.75	7	1.78	1.4		12.3
		Specific gravity	57	0.50	7	0.52	2.8		12.3
	SS	MOR ($\times 10^3$ lb/in^2)	151	5.81	4	5.23	– 10.0	– 25.4	2.6
		MOE ($\times 10^6$ lb/in^2)	151	2.16	4	2.50	15.4		2.6
		Specific gravity	151	0.51	4	0.59	14.5		2.6
All		MOR	568		24				4.2
		MOE	484		21				4.3

[a] No apparent damage defect involved in failure.
[b] Other mechanical damage defect involved in failure.
[c] Percentage of pieces with nail hole defects involved in failure out of all pieces within size–grade group.
[d] Difference of mean (%) MOR is (defect – no defect) / (no defect).
[e] Difference of mean (%) MOR adjusted for MOE is [(MOR defect – MOR no defect) / MOR no defect] – [(MOE defect – MOE no defect) / MOE no defect].

damage failures, and about 5% more slope of grain failures than the GDDs would indicate.

When comparing mean MOR, data were sorted in two groups, one in which the failure defect matched the grade-determining defect and another that did not. This was done to obtain a measure of how much strength could differ, according to failure type, depending on whether or not the GDD caused failure. In theory, the group that failed by the grade-determining defect should exhibit lower MOR, assuming SG is similar.

Mean MOR and SG are reported according to failure type and whether or not the failure defect matched the visual GDD. Tables 29, 30, and 31 indicate this comparison for the three sizes of lumber. The following observations are made:

Tension-wood failures are typically in clear wood with no defects involved. These group means compare very well to the comparable size SS overall group averages (Table 8); mean MORs of 7.07, 6.14, and 5.97 $\times 10^3$ lb/in^2 compared to 7.03, 6.11, and 5.65 $\times 10^3$ lb/in^2 for the 2 by 6, 2 by 8, and 2 by 10 sizes, respectively.

Differences in MOR for boards with knot failures to boards whose grade-determining defect were knots are 0.64, 0.79, and 0.81 $\times 10^3$ lb/in^2 for the 2 by 6, 2 by 8, and 2 by 10 sizes, respectively.

Mean MOR for boards with horizontal shear failures were higher than the overall mean MOR for the 2 by 6 (9.40 $\times 10^3$ lb/in^2 compared with 5.28 $\times 10^3$ lb/in^2) and 2 by 8 (5.80 $\times 10^3$ lb/in^2 compared with 4.79 $\times 10^3$ lb/in^2) sizes and right at the mean for the 2 by 10 (4.03 $\times 10^3$ lb/in^2 compared with 4.04 $\times 10^3$ lb/in^2) size.

Boards with compression failures exhibited a greater mean MOR than the overall mean MOR for all sizes.

Table 26—Distribution of failure codes for No. 2 lumber

Failure code (Table 2)	All sizes and locations		2 by 6						2 by 8				2 by 10			
			Fort Ord		Oakland		Washington		Fort Ord		Washington		Oakland		Minnesota	
	N	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%
Tension-wood (1)	58	13.2	10	14.1	2	12.5	3	15.0	29	14.6	7	16.3	5	9.4	2	5.0
Tension-knot (2)	234	53.1	40	56.3	8	50.0	14	70.0	102	51.5	25	58.1	25	47.2	20	50.0
Tension-damage (3)	36	8.2	5	7.0	3	18.8	1	5.0	10	5.1	7	16.3	5	9.4	5	12.5
Tension-SOG (4)	56	12.7	10	14.1	2	12.5	—	—	27	13.6	1	2.3	9	17.0	7	17.5
Compression (5)	21	4.8	2	2.8	1	6.3	2	10.0	11	5.6	—	—	4	7.5	1	2.5
Horizontal shear (6)	32	7.3	3	4.2	—	—	—	—	16	8.1	3	7.0	5	9.4	5	12.5
Invalid test (7)	2	0.5	—	—	—	—	—	—	2	1.0	—	—	—	—	—	—
Other (8)	2	0.5	1	1.4	—	—	—	—	1	0.5	—	—	—	—	—	—
Total	441	100	71	100	16	100	20	100	198	100	43	100	53	100	40	100

Table 27—Distribution of grade determining defects (GDD) of No. 2 lumber

GDD (code)	All sizes and locations		2 by 6						2 by 8				2 by 10			
			Fort Ord		Oakland		Washington		Fort Ord		Washington		Oakland		Minnesota	
	N	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%
Shake (1)	31	7.3	3	4.2	—	—	—	—	12	6.1	3	7.0	11	20.8	2	8.0
Splits (2)	11	2.6	1	1.4	—	—	1	5.0	7	3.5	—	—	—	—	2	8.0
Knots (3)	173	40.6	32	45.1	9	56.3	16	80.0	69	34.8	28	65.1	7	13.2	12	48.0
Damage (5)	147	34.5	29	40.8	3	18.8	2	10.0	84	42.4	7	16.3	18	34.0	4	16.0
Wane (6)	5	1.2	—	—	1	6.3	—	—	1	0.5	1	2.3	1	1.9	1	4.0
Slope of grain (7)	30	7.0	1	1.4	2	12.5	—	—	8	4.0	2	4.7	16	30.2	1	4.0
Warp (8)	1	0.2	1	1.4	—	—	—	—	—	—	—	—	—	—	—	—
Checks (9)	2	0.5	—	—	—	—	—	—	2	1.0	—	—	—	—	—	—
Other (10)	26	6.1	4	5.6	1	6.3	1	5.0	15	7.6	2	4.7	—	—	3	12.0
Total	426	100	71	100	16	100	20	100	198	100	43	100	53	100	25	100

Tension at knot failures have the lowest mean MOR for the 2 by 6 and 2 by 8 sizes and the second lowest (slope of grain failures were weaker) for the 2 by 10 sizes. In all cases, MOR for boards failing at knots in tension is about 80% of the overall group mean.

Select Structural Grade

The frequency of the various failure types for all sizes of the SS grade is shown in Table 31. Knot-related tension failures dominate at about 33%, with clear-wood tension failure following at about 17%. Interestingly, horizontal shear failures occurred about 7% of the time in the No. 2 grade, but increased to about 12% in the SS grade for all sizes. However, shear failures were as high as 18% for the 2 by 10 SS (Table 32). Horizontal shear failures are known to be relatively infrequent in testing mill-produced lumber (~1% to 2% of the time), so either the shear strength may be reduced or, more likely, splitting from damage and drying has resulted in a greater frequency of this type of failure. We will discuss this in detail later.

The frequency of failures from damage also increased in the SS grade, up from about 8% in the No. 2 grade to about 14% in the SS grade. This makes sense, as the fewer natural defects in the higher grade increase the likelihood of damage in board failure.

Mean MOR and SG are also reported by failure type for the SS boards. The following observations are made:

- Compression failures have the greatest mean MOR for the 2 by 6 and 2 by 8 groups, and the second greatest for the 2 by 10 group.
- Knot failures in tension have the lowest mean MOR for all sizes.

Table 28—Mean properties by failure code for 2 by 6 No. 2 grade

Failure code (Table 2)	Same as visual grade (GDD[a])	Mean[b] MOR ($\times10^3$ lb/in^2)	Mean[b] SG[c]	All locations *N*	All locations %	Fort Ord *N*	Fort Ord %	Oakland *N*	Oakland %	Washington *N*	Washington %
Tension-wood (1)	N	7.07	0.497	15	14.2	10	14.3	2	12.5	3	15.0
Tension-knot (2)	N	4.59	0.489	19	17.9	14	20.0	2	12.5	3	15.0
	Y	3.95	0.487	43	40.6	26	37.1	6	37.5	11	55.0
	Combined	4.15	0.488	62	58.5	40	57.1	8	50.0	14	70.0
Tension-damage (3)	N	6.60	0.471	4	3.8	2	2.9	1	6.3	1	5.0
	Y	6.88	0.476	5	4.7	3	4.3	2	12.5	—	—
	Combined	6.75	0.473	9	8.5	5	7.1	3	18.8	1	5.0
Tension-slope-of-grain (4)	N	6.01	0.488	9	8.5	9	12.9	—	—	—	—
	Y	4.03	0.569	3	2.8	1	1.4	2	12.5	—	—
	Combined	5.51	0.508	12	11.3	10	14.3	2	12.5	—	—
Compression (5)	N	8.86	0.535	3	2.8	2	2.9	1	6.3	—	—
	Y	5.99	0.636	2	1.9	—	—	—	—	2	10.0
	Combined	7.71	0.575	5	4.7	2	2.9	1	6.3	2	10.0
Horizontal shear (6)	N	9.40	0.551	3	2.8	3	2.9	—	—	—	—
Total		5.28	0.496	106	100	70	100	16	100	20	100

[a] Grade-determining defect.
[b] Means shown are same as reported in Table 8.
[c] Specific gravity.

Table 29—Mean properties by failure code for 2 by 8 No. 2 grade

Failure code (Table 2)	Same as visual grade (GDD[a])	Mean[b] MOR ($\times10^3$ lb/in^2)	Mean[b] SG[c]	All locations *N*	All locations %	Fort Ord *N*	Fort Ord %	Washington *N*	Washington %
Tension-wood (1)	N	6.14	0.478	35	14.8	29	14.9	6	14.0
Tension-knot (2)	N	4.28	0.468	64	27.0	56	28.9	8	18.6
	Y	3.49	0.466	63	26.6	46	23.7	17	39.5
	Combined	3.89	0.467	127	53.6	102	52.6	25	58.1
Tension-damage (3)	N	4.70	0.509	11	4.6	5	2.6	6	14.0
	Y	5.06	0.503	6	2.5	5	2.6	1	2.3
	Combined	4.83	0.507	17	7.2	10	5.2	7	16.3
Tension-slope-of-grain (4)	N	5.48	0.513	22	9.3	21	10.8	1	2.3
	Y	4.76	0.515	6	2.5	5	2.6	1	2.3
	Combined	5.33	0.513	28	11.8	26	13.4	2	4.7
Compression (5)	N	7.18	0.475	11	4.6	11	5.7		
Horizontal shear (6)	N	6.03	0.493	15	6.3	14	7.2	1	2.3
	Y	4.96	0.523	4	1.7	2	1.0	2	4.7
	Combined	5.80	0.500	19	8.0169	16	8.25	3	6.98
Total		4.79	0.480	237	100	194	100	43	100

[a] Grade-determining defect.
[b] Means shown are same as reported in Table 8.
[c] Specific gravity.

Table 30—Mean properties by failure code for 2 by 10 No. 2 grade

Failure code (Table 2)	Same as visual grade (GDD[a])	Mean[b] MOR ($\times 10^3$ lb/in^2)	Mean[b] SG[c]	All locations *N*	All locations %	Oakland *N*	Oakland %	Minnesota *N*	Minnesota %
Tension-wood (1)	N	5.97	0.531	5	7.5	4	8.9	1	4.5
Tension-knot (2)	N	3.77	0.497	22	32.8	14	31.1	8	36.4
	Y	2.96	0.492	16	23.9	11	24.4	5	22.7
	Combined	3.43	0.495	38	56.7	25	55.6	13	59.1
Tension-damage (3)	N	4.38	0.488	5	7.5	3	6.7	2	9.1
	Y	5.18	0.504	4	6.0	2	4.4	2	9.1
	Combined	4.74	0.495	9	13.4	5	11.1	4	18.2
Tension-SOG[d] (4)	N	3.34	0.525	11	16.4	9	20.0	2	9.1
Compression (5)	N	8.66	0.583	2	3.0	2	4.4		0.0
	Y	6.00	0.540	2	3.0	2	4.4		0.0
	Combined	7.33	0.562	4	6.0	4	8.9	0	0.0
Horizontal shear (6)	N	4.61	0.493	5	7.5	2	4.4	3	13.6
	Y	3.32	0.476	4	6.0	3	6.7	1	4.5
	Combined	4.03	0.485	9	13.4	5	11.1	4	18.2
Total		4.04	0.494	67	100	45	100	22	100

[a] Grade-determining defect.
[b] Means shown are same as reported in Table 8.
[c] Specific gravity.
[d] Slope of grain.

Table 31—Distribution of failure codes for SS lumber

Failure code (Table 2)	All sizes and locations		2 by 6						2 by 8				2 by 10			
			Fort Ord		Oakland		Washington		Fort Ord		Washington		Oakland		Minnesota	
	N	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%	*N*	%
Tension-wood (1)	94	17.1	4	33.3	16	34.0	10	27.0	6	16.2	28	22.2	17	8.6	13	13.8
Tension-knot (2)	184	33.5	1	8.3	6	12.8	12	32.4	5	13.5	67	53.2	50	25.4	43	45.7
Tension-damage (3)	79	14.4	1	8.3	11	23.4	4	10.8	4	10.8	19	15.1	36	18.3	4	4.3
Tension-SOG[a] (4)	70	12.7	4	33.3	8	17.0	4	10.8	8	21.6	5	4.0	28	14.2	13	13.8
Compression (5)	50	9.1	2	16.7	4	8.5	3	8.1	8	21.6	4	3.2	22	11.2	7	7.4
Horizontal shear (6)	65	11.8	—	—	2	4.3	3	8.1	6	16.2	2	1.6	39	19.8	13	13.8
Invalid test (7)	1	0.2	—	—	—	—	1	2.7	—	—	—	—	—	—	—	—
Other (8)	7	1.3	—	—	—	—	—	—	—	—	1	0.8	5	2.5	1	1.1
Total	550	100	12	100	47	100	37	100	37	100	126	100	197	100	94	100

[a] Slope-of-grain.

Table 32—Mean properties by failure code and size for Select Structural (SS) grade

Size	Failure code (Table 2)	Mean [a] MOR ($\times 10^3$ lb/in^2)	Mean [a] SG	All locations N	All locations %	Fort Ord N	Fort Ord %	Oakland N	Oakland %	Washington N	Washington %	Minnesota N	Minnesota %
2 by 6	Tension-wood (1)	7.48	0.52	30	31.6	4	33.3	16	34.0	10	27.8	—	—
	Tension-knot (2)	5.14	0.51	19	20.0	1	8.3	6	12.8	12	33.3	—	—
	Tension-damage (3)	7.20	0.54	16	16.8	1	8.3	11	23.4	4	11.1	—	—
	Tension-SOG[b] (4)	6.68	0.49	16	16.8	4	33.3	8	17.0	4	11.1	—	—
	Compression (5)	9.43	0.51	9	9.5	2	16.7	4	8.5	3	8.3	—	—
	Horizontal shear (6)	7.75	0.56	5	5.3	0	0.0	2	4.3	3	8.3	—	—
	Total	7.03a	0.52[a]	95	100	12	100	47	100	36	100	—	—
2 by 8	Tension-wood (1)	6.71	0.50	34	21.0	6	16.2	—	—	28	22.4	—	—
	Tension-knot (2)	5.36	0.48	72	44.4	5	13.5	—	—	67	53.6	—	—
	Tension-damage (3)	6.17	0.51	23	14.2	4	10.8	—	—	19	15.2	—	—
	Tension-SOG (4)	5.77	0.51	13	8.0	8	21.6	—	—	5	4.0	—	—
	Compression (5)	8.67	0.51	12	7.4	8	21.6	—	—	4	3.2	—	—
	Horizontal shear (6)	6.55	0.52	8	4.9	6	16.2	—	—	2	1.6	—	—
	Total	6.11a	0.49[a]	162	100	37	100	—	—	125	100	—	—
2 by 10	Tension-wood (1)	6.68	0.52	30	10.3	—	—	17	8.6	—	—	13	13.8
	Tension-knot (2)	4.56	0.49	93	32.0	—	—	50	25.4	—	—	43	45.7
	Tension-damage (3)	5.49	0.53	40	13.7	—	—	36	18.3	—	—	4	4.3
	Tension-SOG (4)	5.55	0.52	41	14.1	—	—	28	14.2	—	—	13	13.8
	Compression (5)	7.44	0.54	29	10.0	—	—	22	11.2	—	—	7	7.4
	Horizontal shear (6)	5.95	0.52	52	17.9	—	—	39	19.8	—	—	13	13.8
	Other (8)	7.84	0.51	6	2.1	—	—	5	2.5	—	—	1	1.1
	Total	5.65	0.51[a]	291	100	—	—	197	100	—	—	94	100

[a] Means shown are same as reported in Table 8.
[b] Slope of grain.

- About 18% (52 of 291) of the 2 by 10s failed in horizontal shear; however, these boards exhibited a greater MOR than the rest of the 2 by 10s (5.95 $\times 10^3$ lb/in^2 compared with 5.65 $\times 10^3$ lb/in^2).

Analysis of Full-Size Lumber by Grade

Up to this point, all analyses were by grade and size. No adjustments were made to the data other than to correct for MC. Though useful information was developed, analyzing cells of data by size and grade resulted in data sets that could be rather small and reduced the statistical confidence of the results. In this section, the full-size lumber data have been adjusted to a common size (2 by 8) and a variety of analyses performed. Whereas some of these analyses duplicate those performed earlier, they involve more data and should provide more confidence in the results. No adjustments for location or SG were made. Only MOR is reported.

As indicated in Table 33, a comparison of the bending strength of all lumber, the combined Douglas-fir and larch (L) data and lumber of other species is made. Results indicate that the mean MOR of the all grades/sizes data set is only about 2% lower than the DF/L alone. Further, a statistical significance test indicates that the Douglas-fir and larch lumber MOR is significantly different than the other species MOR. A statistical significance test to compare the all grades/sizes data set and the Douglas-fir and larch data set would be illogical because the Douglas-fir and larch data are a subset of the all grades/sizes data set. Assuming that the species variability found in this study is representative of other deconstruction sites, these results indicate that the inclusion of species other than Douglas-fir and larch (at least up to the proportion present in this data set) does not appreciably affect either the mean or 5th percentile MOR estimate of the whole population of lumber.

Table 34 indicates the results of analyzing all the full-size lumber data by grade. As expected, there is a significant difference in the mean and 5th percentile MOR in the two grades, with the SS grade significantly higher than the No. 2 grade.

Table 35 shows the results of sorting the size-adjusted full-size lumber data by failure type. As indicated in the table,

Table 33—Bending strength of reclaimed lumber by species mixed size[a] and grade

	N	Mean MOR ($\times10^3$ lb/in^2)	Statistical difference	5th percentile MOR ($\times10^3$ lb/in^2)	Statistical difference
All grades, sizes	1,078	5.56		2.36	
DF/L[b]	991	5.64	*A*[c]	2.45	*A*[b]
Other species	87	4.61	*B*[c]	1.49	*B*[b]

[a] All full-size lumber data adjusted to 2 by 8 size.
[b] Douglas-fir and larch.
[c] Differences indicate a significance level at < 0.0001.

Table 34—Bending strength of all sizes by grade, Douglas-fir and larch only

	N	Mean MOR ($\times10^3$ lb/in^2)[a]	Statistical difference	5th percentile MOR ($\times10^3$ lb/in^2)
SS	550	6.32	*A*[b]	3.09
No. 2	441	4.79	*B*[b]	2.09

[a] All full-size lumber data adjusted to 2 by 8 size.
[b] Differences indicate a significance level at < 0.0001.

lumber exhibiting compression failures resulted in the highest MORs, followed by wood tension, shear, damage, SOG, and knots. This ranking was consistent for both grades and when grades were mixed. As was indicated in earlier analysis, knot failures are the critical lumber characteristic in terms of bending strength. Note also that knot failures are the most common failure type, making up nearly half the failures. As a group, SOG failures produce the second lowest MORs, likely due to the effect of splits on strength. Also, note that shear failures are common, making up about 9% of all failures. Shear failures made up about 12% of failures in the SS grade and a much lower 6% in the No. 2 grade. These findings are consistent with the results of the earlier analysis by size and grade.

Table 36 groups the bending strength of size-adjusted full-sized reclaimed lumber by GDD. Because the lumber in the SS grade had no GDD, only the No. 2 grade is shown. Interestingly, the lowest strength boards were those that had splits as the GDD. The next lowest in strength are knots. This is reasonably consistent with the findings of Table 36. Damage determined grade for almost half the No. 2 grade; however, damage was involved in the failure for 9% of the lumber. This might suggest that the grading for damage is too conservative.

Conclusions

Based on the analysis of test data generated from both small clear specimen testing and full-sized lumber tests, several conclusions can be drawn.

Clear Wood Properties

Based on the analysis of the calculated properties for the small clear bending test specimens cut from reclaimed Douglas-fir dimensional lumber—

1. Mean bending strength (MOR) was essentially the same as that of historical data.
2. Mean SG was essentially the same as that in historical data.
3. Mean MOE was about 10% greater than that in historical data.
4. Differences in MOR between groups of lumber from different locations can be explained by differences in SG.

Based on these observations, we conclude that MOR and MOE of clear wood appear to be unaffected by aging and previous load history.

Full-Size Lumber Properties

Based on the analysis of the calculated properties from the bending tests of reclaimed Douglas-fir dimensional lumber—

1. Mean bending strength (MOR) was about 25% lower than in-grade test data.
2. Mean stiffness (MOE) was about 10% higher than in-grade test data.
3. Existing size-effect equations are applicable for reclaimed lumber.
4. No geographical location effect was found for the four locations tested.
5. Nail holes become influential to MOR when they were closely spaced or if they had created further splitting, primarily when located at the high-stress tension edge.
6. Shear failures were found to be relatively common in testing reclaimed lumber, though the bending strength of this lumber was higher than lumber failing at knots.

Table 35—Bending strength of Douglas-fir and larch by failure type

	All grades		SS		No. 2	
Failure type	*N*	MOR ($\times 10^3$ lb/in^2)[a]	*N*	MOR ($\times 10^3$ lb/in^2)[a]	*N*	MOR ($\times 10^3$ lb/in^2)[a]
Compression	71	8.20	50	8.52	21	7.43
Wood tension	152	6.75	94	7.06	58	6.25
Shear	97	6.33	65	6.71	32	5.56
Damage	115	6.00	79	6.27	36	5.42
SOG[b]	126	5.60	70	6.15	56	4.92
Knot	418	4.48	184	5.21	234	3.91

[a] All full-size lumber data adjusted to 2 by 8 size.
[b] Slope of grain.

Table 36—Bending strength of No. 2 lumber by grade determining defect (GDD), Douglas-fir and larch only

	No. 2 grade	
GDD	*N*	MOR ($\times 10^3$ lb/in^2)[a]
Wane	5	6.74
Bolt holes	0	0
Other (skip, narrow, etc.)	26	6.22
Damage	147	5.40
Shake	31	5.21
SOG	30	4.36
Knots	173	4.07
Splits	11	3.93
Drying checks	2	2.78

[a]All full-size lumber data adjusted to 2 by 8 size.

7. The frequency of lumber failures involving damage were less common than lumber with damage as the grade-determining defect, suggesting that grading may be too conservative regarding damage. In addition, lumber failing at points of damage exhibited higher bending strength than lumber failing at knots. Additionally, the frequency of failures at points of damage was higher for SS than No. 2 grades.

Recommendations

The following recommendations are made with respect to the regrading and reuse of salvaged lumber:

1. Reclaimed lumber should be regraded before reuse. Grading rules, and possibly design guidelines, should formally recognize this material and provide guidance regarding appropriate reuse.

2. Any requirements for reuse should recognize the impracticality of identifying the exact species of each piece of 2-by lumber salvaged and accommodate some degree of species mixing.

3. Regular edge-nail holes should be placed in the compression zone, or away from the highest tension zone in design.

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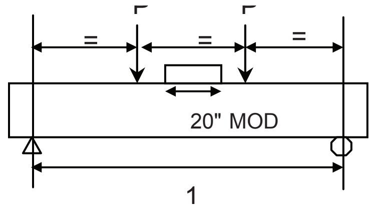
Appendix—Reclaimed Lumber Test Worksheet

General Information

Setup



Size: 2x8
Species: Douglas-fir
Location: Washington

EML #: 20005_B5
Test #: ____
Date: ____
Specimen #: ____

Nail Holes

	Orientation			Spacing
Nail Holes:	Up	Down	None	____

Worst Flaw

	Orientation			Type
Visual	Up	Down	None	____
Failure Causing	Up	Down	None	____

Dimensions

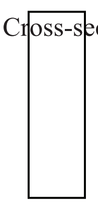
b = ____ in.
h = ____ in.
L = ____ in.
Sag = ____ in.

Failure Information

Failure Code: ____

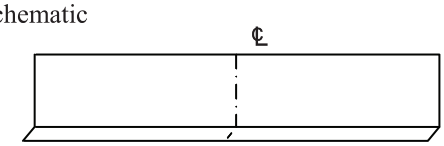
Third Point Bending Macro Output

Cross-section



Time = ____ seconds
Pmax= ____ kips
MOR = ____ lb/in.^{2}
r^2= ____
# points = ____
SEE = ____ lb/in.^{2}
MOE = ____ ksi*103

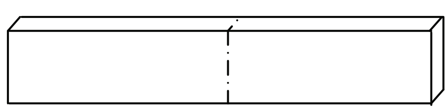
Board Schematic



Splits

Edge: None Some Severe
Face : None Some Severe

Opposite Face



Moisture Meter ____ %

Comments