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# Mechanical Grading of 6-Inch-Diameter Lodgepole Pine Logs for the Travelers' Rest and Rattlesnake Creek Bridges

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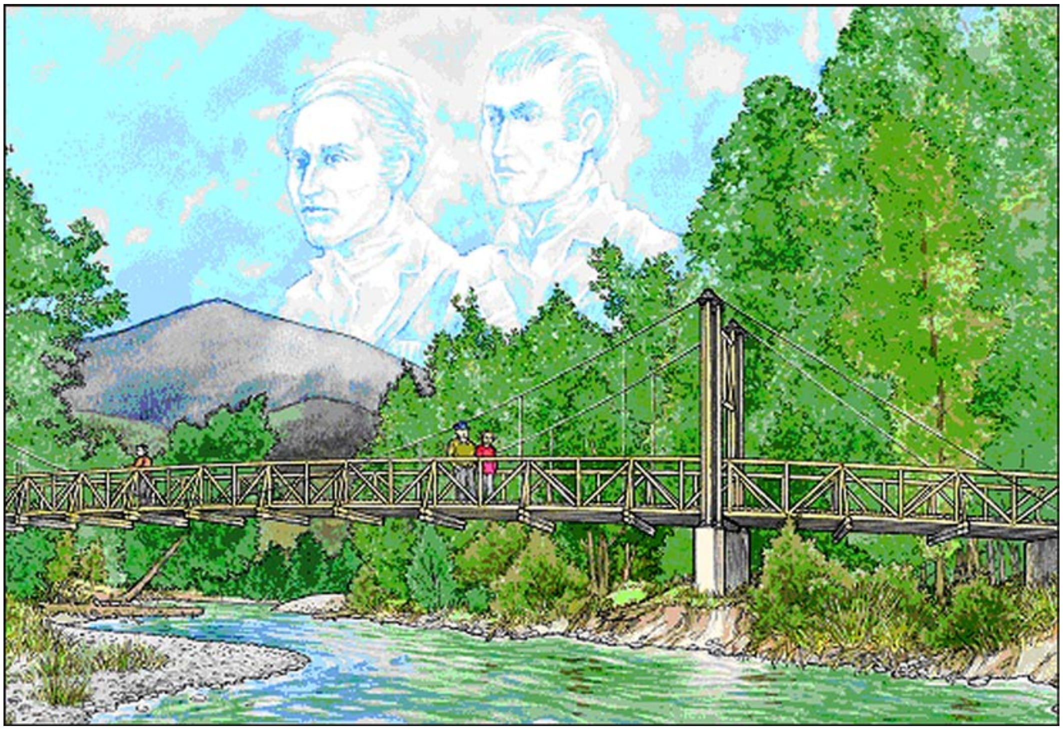

# Abstract

Forest Products Laboratory (FPL) assistance was requested in mechanical grading of logs for two cable suspension bridges intended for pedestrian use in parks near Missoula, Montana. Two hundred ninety two lodgepole pine logs were obtained from a beetle-killed stand near Elk City, Idaho, by Porterbuilt, Inc., of Hamilton, Montana, and machined (dowelled) to a constant diameter of 6 in. The logs were visually graded by Timber Products Inspection, Inc., of Longview, Washington, and mechanically graded by FPL staff using procedures developed in previous research. Of the logs selected, 236 (80.8%) made at least No. 3 visual grade and were thus eligible for mechanical grading. Two hundred fifteen of the logs (74% of total) made a mechanical grade having an allowable bending strength–MOE assignment of 2150 Fb–1.4E, 21 of the logs (7%) that failed to make this mechanical grade could still maintain the assigned visual grade, and 56 logs (19%) would have to be used in non-structural applications. By comparison, of the 236 logs that made at least No. 3 visual grade, 188 (64%) graded as TP No.1, which is assigned allowable properties of 1250 Fb–1.1E. Thus mechanical grading is shown to provide a more efficient property assignment than does visual grading.

Keywords: mechanical grading, lodgepole pine, logs, timber bridge

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**SI conversion**

| Inch–pound unit | Multiply by | SI unit |
|---|---|---|
| inch (in.) | 25.4 | millimeter (mm) |
| foot | 0.3048 | meter |
| $\text{lb/in}^2$ | 0.45366.894 | kilopascal (kPa) |

$T_{°C} = (T_{°F} - 32)/1.8$

# Contents

# Executive Summary

## Background

Beaudette Consulting Engineers (BCE) of Missoula, Montana, requested assistance from the Forest Products Laboratory (FPL), Madison, Wisconsin, in mechanically grading lodgepole pine logs to use in building two cable suspension bridges in western Montana. The grading project is a demonstration of a proposed mechanical grading system developed by FPL in cooperative research studies with Timber Products Inspection, Inc. (TP), of Conyers, Georgia, and the University of Idaho in Moscow, Idaho. Bridge design and selection of log design values are the responsibility of the engineering consulting firm.

## Objectives

The project's objective is to provide the engineering firm with a variety of grade options for using small-diameter lodgepole pine logs more efficiently in these two engineered roundwood structures.

## Procedures

The 292 logs obtained for this demonstration were cut from beetle-killed lodgepole pine trees salvaged from a stand near Elk City, Idaho. Candidate logs were pre-selected by BCE prior to processing. The logs were turned to a uniform diameter of 6 in. and cut to lengths specified by BCE at Portbuilt, Inc., in Hamilton, Montana. The logs were visually graded by a TP quality supervisor. Forest Products Laboratory scientists determined the modulus of elasticity (MOE) of all logs in transverse vibration (Etv). Few data exist on the properties of small-diameter lodgepole pine logs machined to a constant diameter. So using available data on 3- to 6-in.-diameter Douglas-fir and ponderosa pine logs, we developed the property relationships needed to assign mechanical grades to the logs in our study. To qualify for a mechanical grade, the logs first had to meet at least a TP No. 3 visual grade. Assignment of a mechanical grade was then based on the measured Etv values, with design values in bending ($F_b$ and MOE), tension parallel to the grain ($F_t$), and compression parallel to the grain ($F_{c\|}$) developed from previous studies. Allowable shear strength ($F_v$) and strength in compression perpendicular to the grain ($F_{c\perp}$) are the same as those assigned by TP to visual grades of lodgepole pine.

## Results

The visual grades of the 292 logs selected for this study were 188 No. 1 (64.4%), 21 No. 2 (7.2%), 27 No. 3 (9.2%), and 56 culls (19.2%). Excessive knot size was the largest single defect type in the cull logs. Thus, 236 of the logs (80.8%) were eligible for mechanical grading. The average moisture content of the logs was 19%.

A discussion of property relationships from the various available data sets and pertinent literature led to the following conclusions concerning assignment of allowable properties. The relationship between static MOE and Etv was shown to be independent of species for 3- to 6-in.-diameter logs machined to a constant diameter. Equation (1) (page 6) for the combined Douglas-fir and ponderosa pine logs is

$$\text{MOE} = 0.891 \times \text{Etv} - 0.001$$

$R^2 = 0.97$, where MOE and Etv values are given in $10^6$ lb/in$^2$.

Two alternatives were developed for estimating the modulus of rupture (MOR). The first was based on the MOR–MOE relationship for ponderosa pine logs machined to constant diameter of 3 to 6 in.

This alternative generally produces a more conservative estimate and is a result of a statistical comparison of equations fit to several alternative data sets. The 90% lower confidence interval of this regression is Equation (7) (page 12):

$$\text{MOR}_{0.901\text{cl}} = 2.323 \times \text{MOE} + 1.850$$

for MOE in $10^6$ lb/in$^2$ and MOR in $10^3$ lb/in$^2$. Limited data on 44 pieces of lodgepole pine machined to a constant diameter of 3.5 in. and technical judgment based on data for 9-in.-diameter logs suggest that a more representative MOE–MOR relationship might be obtained using the combined Douglas-fir and ponderosa pine data for logs machined to a uniform diameter of 3 to 6 in. The 90% lower confidence interval for the second alternative is Equation (8) (page 13):

$$\text{MOR}_{0.901\text{cl}} = 5.125 \times \text{MOE} - 0.532$$

Ultimate compression stress parallel to the grain (UCS) was estimated from a conservative equation fit to data on the bending–compression relationship for 3- to 6-in.-diameter Douglas-fir and ponderosa pine logs with taper (Eq. (6), page 8). This equation is

$$\text{UCS/MOR} = 0.00704(\text{MOR})^2 - 0.1130(\text{MOR}) + 0.750$$

for MOR $\leq 8.018 \times 10^3$ lb/in$^2$ or UCS/MOR = 0.30, for MOR $> 8.081 \times 10^3$ lb/in$^2$.

Very limited data on the ultimate tensile stress parallel to the grain (UTS) of small-diameter lodgepole pine logs suggested that a more conservative procedure be used than the ratio of UTS/MOR = 0.55 (page 8) given in ASTM D 3957. The ratio adopted in this study is UTS/MOR = 0.45, which is the relationship assumed in ASTM D 6570 for mechanically graded dimension lumber. Allowable properties for mechanically graded lodgepole pine logs are developed for a variety of grade combinations. These include combinations where two mechanical grades are produced and some where all logs are graded into one mechanical grade. Only alternatives that involve one mechanical grade are shown in this summary. The combinations involving two grades are

**Potential design values for lodgepole pine logs**

| | | Option 1[a,b] | | | | Option 2[a,b] | | | |
|---|---|---|---|---|---|---|---|---|---|
| Mechanical grade | Number of logs | $F_\text{b}$ (lb/in$^2$) | $F_\text{t}$ (lb/in$^2$) | $F_{\text{c}\parallel}$ (lb/in$^2$) | MOE ($\times 10^6$ lb/in$^2$) | $F_\text{b}$ (lb/in$^2$) | $F_\text{t}$ (lb/in$^2$) | $F_{\text{c}\parallel}$ (lb/in$^2$) | MOE ($\times 10^6$ lb/in$^2$) |
| 1.9E | 26 | 2,600 | 1,150 | 975 | 1.9 | 3,550 | 1,600 | 1,150 | 1.9 |
| 1.8E | 49 | 2,500 | 1,150 | 975 | 1.8 | 3,350 | 1,500 | 1,100 | 1.8 |
| 1.7E | 88 | 2,450 | 1,100 | 950 | 1.7 | 3,150 | 1,400 | 1,100 | 1.7 |
| 1.6E | 147 | 2,350 | 1,050 | 950 | 1.6 | 2,950 | 1,350 | 1,050 | 1.6 |
| 1.5E | 196 | 2,250 | 1,000 | 925 | 1.5 | 2,750 | 1,250 | 1,000 | 1.5 |
| 1.4E | 215 | 2,150 | 950 | 900 | 1.4 | 2,550 | 1,150 | 1,000 | 1.4 |
| 1.3E | 232 | 2,050 | 925 | 900 | 1.3 | 2,350 | 1,050 | 950 | 1.3 |
| 1.2E | 233 | 1,950 | 875 | 875 | 1.2 | 2,150 | 975 | 900 | 1.2 |
| 1.1E | 235 | 1,900 | 850 | 850 | 1.1 | 1,950 | 875 | 875 | 1.1 |
| Original visual grades | | | | | | | | | |
| No. 1 | 188 | 1,250 | 675 | 625 | 1.1 | 1,250 | 675 | 625 | 1.1 |
| No. 2 | 21 | 1,050 | 575 | 525 | 1.1 | 1,050 | 575 | 525 | 1.1 |
| No. 3 | 27 | 600 | 325 | 300 | 0.9 | 600 | 325 | 300 | 0.9 |
| Cull | 56 | — | — | — | — | — | — | — | — |

[a] Option 1 is based only on data for ponderosa pine, and option 2 is based on the combined ponderosa pine and Douglas-fir data.

[b] $F_\text{v}$ = 95 lb/in$^2$ and $F_{\text{c}\perp}$ = 395 lb/in$^2$ for all grades (Log Home Grading Rules (including supplements 1–5). 1995. Timber Products Inspection, Inc., Conyers, Georgia).

summarized beginning on page 10 and are shown in Tables 7 and 8. Design values for visually graded logs are shown for comparison.

## Recommendations

Both alternatives for mechanical grading generally provide grades with design values higher than those assigned through visual grading. If the assigned values developed using the more conservative option 1 are adequate, this would be the preferred alternative. If higher strength values are required, then option 2 could be used. A research study tentatively planned to begin in 2006 should provide conclusive evidence on the effect of species on the MOE–MOR relationship for small-diameter lodgepole pine logs. We do not recommend that the equation presented in this paper be used to assign strength values to individual logs. These procedures are valid only for logs grouped into grades.

# Mechanical Grading of 6-Inch-Diameter Lodgepole Pine Logs for the Travelers' Rest and Rattlesnake Creek Bridges

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## Introduction

The critical structural members for two wooden pedestrian bridges were visually graded by Timber Products Inspection, Inc. (TP), of Conyers, Georgia, and their properties estimated using a proposed mechanical grading system for round structural members developed cooperatively by the Forest Products Laboratory (FPL) in Madison, Wisconsin, and the University of Idaho, Moscow, Idaho. One of these bridges is to be a 165-ft span cable suspension bridge over Lolo Creek at Travelers' Rest State Park, Lolo, Montana, and the other a 120-ft span cable suspension bridge over Rattlesnake Creek in Missoula, Montana. Most structural members are lodgepole pine (*Pinus contorta*) machined to a uniform diameter of 6 in. The primary objective of this report is to summarize the visual and mechanical grading options for the lodgepole pine logs so that the engineering firm can use the logs most efficiently in their bridge design. The paper also documents the first commercial application of mechanical grading to small-diameter logs.

### Travelers' Rest Bridge

From September 9 to 11, 1805, and June 30 to July 3, 1806, Lewis and Clark's Corps of Discovery camped along a creek they called Travelers' Rest. Here they took a needed rest and made sure they were adequately equipped for their journey ahead. The first time they stopped at this creek was in preparation for racing the winter into the Bitterroot Mountains, and the second time was on their return trip prior to splitting the party for exploratory jaunts to the Great Falls of the Missouri (Lewis) and the Yellowstone River region (Clark). This small cross-roads campsite is of special historical importance because it is one of only two places along the Lewis and Clark journey where physical evidence verifies their presence.

Travelers' Rest State Park is located about 10 miles south of Missoula, Montana, near the intersection of Highways 93 and 12. It is a relatively new park, with park offices and facilities that opened in 2003. Plans for the park include the establishment of areas telling the story of the Lewis and Clark Expedition, the Native American presence, the experiences of the pioneer homesteads, and the natural history of the area (Fig. 1). A parking lot will be established on the west side of what we now call Lolo Creek, with the historical areas on the other side. A bridge will be constructed across Lolo Creek to minimize environmental damage and to connect the parking lot to the historical areas.

The Travelers' Rest bridge was designed by the engineering firm. It will be a 165-ft cable suspension bridge with a main span of 110 ft and side spans of 27.5 ft (Fig. 2). Forest Service experience has shown that the tops and bottoms of posts in the towers of suspension bridges are very vulnerable to decay. Sometimes an entire bridge must be taken down to repair a tower post. An innovative solution is a composite tower composed of four logs for each of the four cable support towers. Only two logs per tower will be required to support the bridge; therefore, it will allow an individual log to be removed for repair or replacement.

### Rattlesnake Creek Bridge

The Upper Rattlesnake Creek Bridge will be part of the City of Missoula trail system. It will connect the Duncan Drive terminus on the west side of Rattlesnake Creek with the city's trail system on the east side of the creek (Fig. 3). The east side trail system connects with the Rattlesnake National Recreational Area within the Lolo National Forest. The bridge is in an area of very high recreational use and will have high public visibility.

The Rattlesnake Creek Bridge was also designed by the engineering firm. It will be a 120-ft-span cable suspension bridge with a main span of 80 ft and back spans of 20 ft (Fig. 4). The bridge is designed to support the dead load for the main span. Constructed and placed on the abutments,

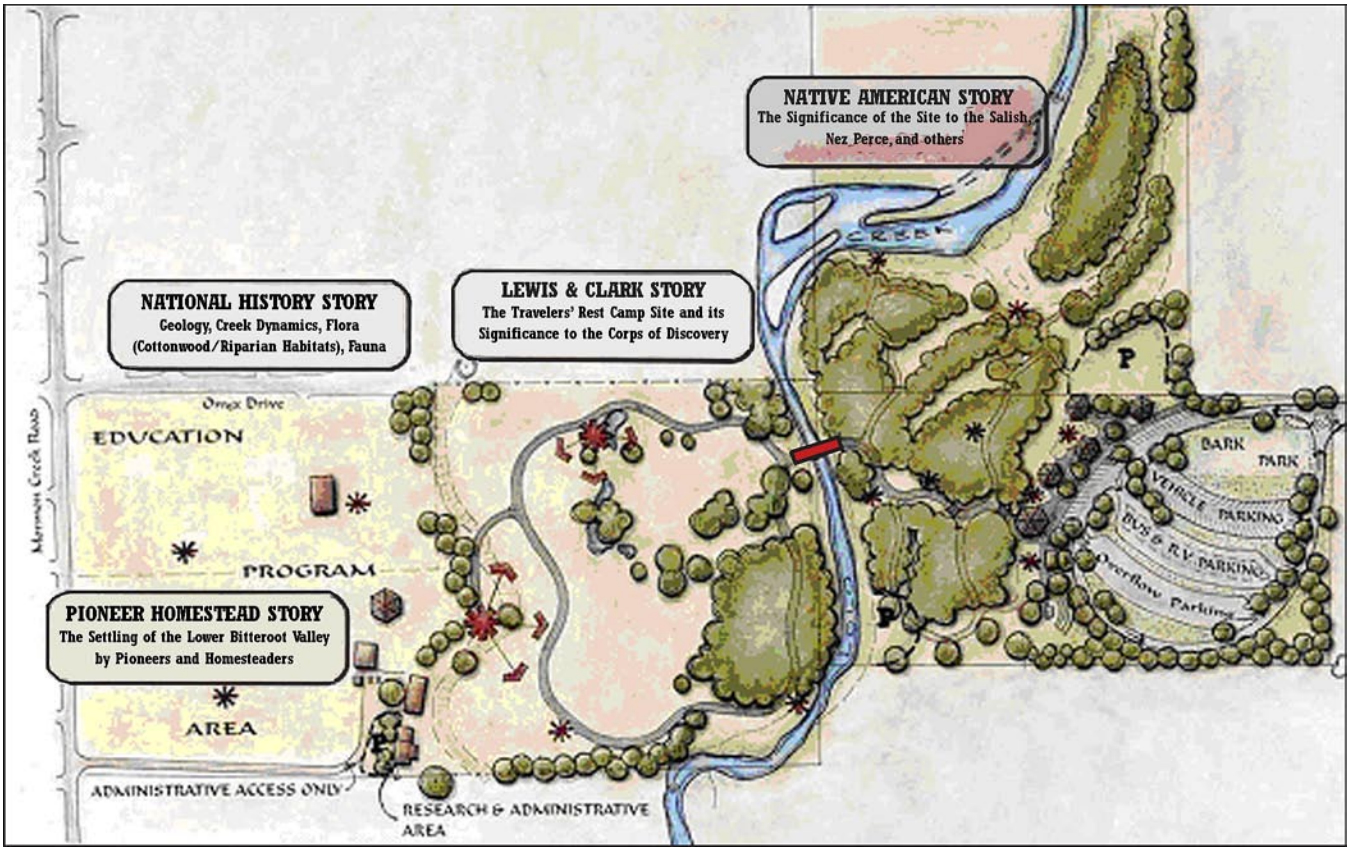

**Figure 1—Conceptual master plan for Travelers' Rest State Park, Lolo, Montana.**

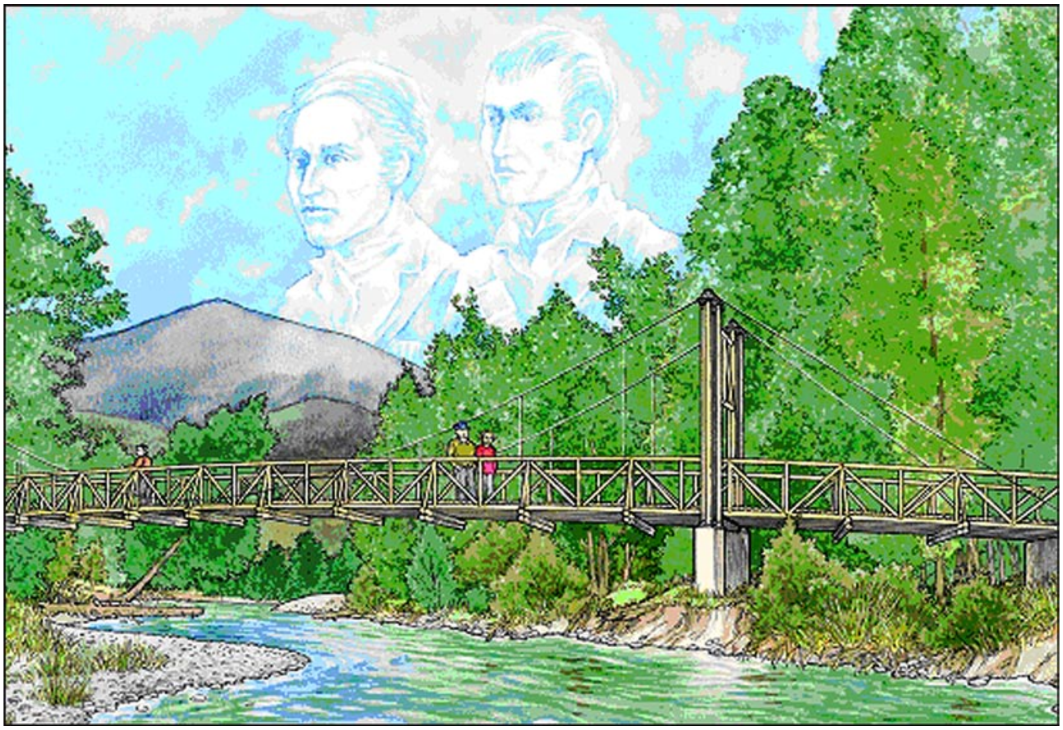

**Figure 2—Cable suspension bridge planned for Travelers' Rest State Park, Lolo, Montana.**

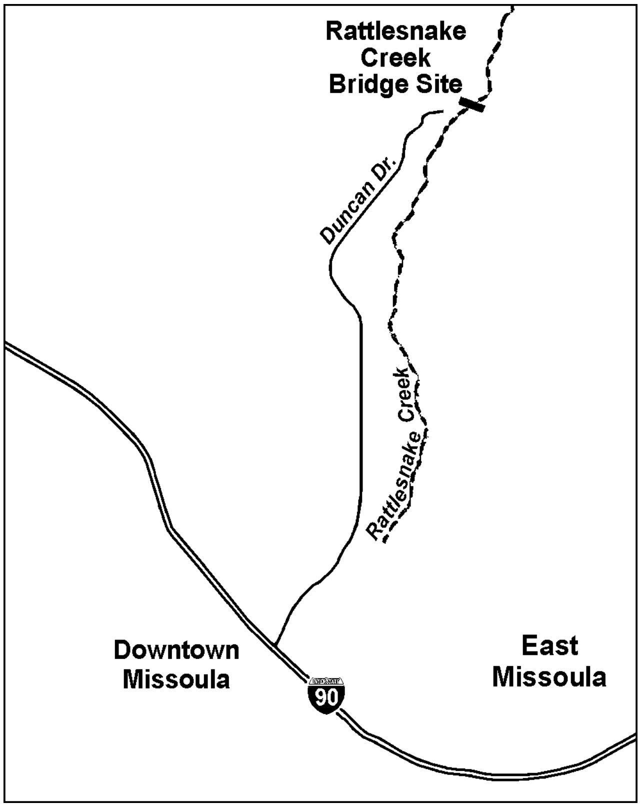

**Figure 3—Location of Rattlesnake Creek Bridge site northeast of Missoula, Montana.**

the cable stays will be attached to support the required live loads. All bridge components will be composed of 6-in.-diameter lodgepole pine logs machined to a uniform cross-section. Towers for the cable will be 10-in.-diameter lodgepole pine.

## Background

### Visual Grading and Property Assignment of Logs by ASTM D 3957

ASTM D 3957, *Standard Practices for Establishing Stress Grades for Structural Members Used in Log Buildings*, was first approved in 1980, with the current revision adopted in 1993 (ASTM 2004). In addition to wall logs, two types of structural round timbers are used in log home construction: unsawn and sawn round timbers (TP 1995). Unsawn round timbers are primarily intended for bending or truss members. Sawn round timbers may have a flattened surface that is sawn or shaved along one side and are also primarily intended for use as bending members. The sawn surface is limited to a penetration of no more than 0.30 of the radius of the round log. This limits the reduction in the cross section to less than 10%. Timber Products Inspection, Inc., has developed structural grading rules for No. 1, 2, and 3 grades of sawn round timbers (TP 1995). A flattened surface on one side is not a grade requirement for "sawn round timber." A round log can be graded as No. 1, 2, or 3, but the allowable properties would be derived assuming that the flattened surface was present. Logs of all grades may also be used as compression members, but the logs for this usage do not usually have a flattened surface. As with visually graded dimension lumber or structural timbers, the grade description of structural logs is a combination of limits on characteristics that affect strength and possibly serviceability for the intended application. Table 1 summarizes the limits on knot size and slope of grain for four TP grades. In addition, there are limits on potential decay associated with knots, shake, splits, and compression wood. Examples of serviceability factors include limits on lack of "roundness" and excessive warp and wane. All these visual grades are suitable for use in timber bridges if they have allowable properties high enough for the intended application.

**Table 1—Limits on knot size and slope of grain and allowable properties for visually graded lodgepole pine structural round timbers[a]**

| Grade[b] | Maximum knot size (in. diameter) | Maximum slope of grain | Allowable properties[c] $F_b$ | $E$ | $F_c$ |
|---|---|---|---|---|---|
| Unsawn | 1/2 | 1:15 | 1,500 | 1.1 | 775 |
| No. 1 | 1/3 | 1:14 | 1,250 | 1.1 | 625 |
| No. 2 | 1/2 | 1:10 | 1,050 | 1.1 | 525 |
| No. 3 | 3/4 | 1:6 | 600 | 0.9 | 300 |

[a] TP (1995). Rules apply to all diameters.
[b] Other limits on grade characteristics are given in TP (1995).
[c] $F_b$, fifth percentile MOR/2.1 (lb/in$^2$); $E$, mean MOE ($10^6$ lb/in$^2$).

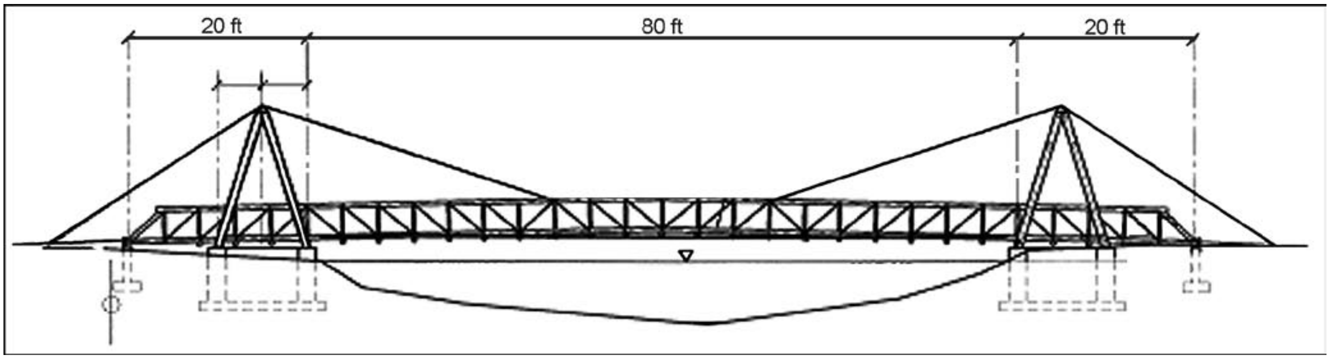

**Figure 4—Schematic drawing of the Rattlesnake Creek Bridge.**

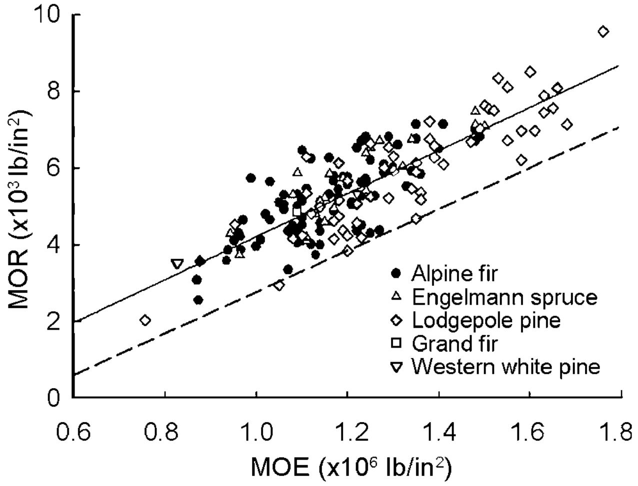

**Figure 5—Relationship between modulus of rupture (MOR) and modulus of elasticity (MOE) for 9-in.-diameter dry logs of the Englemann spruce–Alpine fir–lodgepole pine species group (Green and others, in preparation). (Solid line is mean trend, and dotted line is 90% lower confidence interval.)**

Allowable properties for sawn round timbers are derived from clear wood data, modified by strength ratios set forth in ASTM D 3957 and D 2899 (ASTM 2004). This clear wood approach is therefore very similar to the ASTM D 245 (ASTM 2004) procedures once used to derive allowable properties for all dimension lumber in the United States and still used for structural timbers. Allowable properties in bending ($F_b$), modulus of elasticity (MOE), and compression parallel to grain ($F_{c||}$) for lodgepole pine are also given in Table 1. Allowable properties of visually graded lodgepole pine are also established for tensile strength parallel to grain, strength in compression perpendicular to grain, and shear strength parallel to grain.

## Technical Basis for Mechanical Grading of Small-Diameter Logs

The proposed mechanical grading system for the 6-in.-diameter lodgepole pine logs requires the following:

1. Establishment of a relationship between modulus of elasticity in transverse vibration (Etv) and static modulus of elasticity (MOE)
2. Establishment of a relationship between modulus of rupture (MOR) and MOE
3. Establishment of a relationship between ultimate compression stress parallel to the grain (UCS) and MOR
4. Procedures for estimating other allowable properties

The background for establishment of the required relationships will be summarized in this section.

A study was initiated in 2000 to develop the technical basis for a mechanical grading system for round timbers, primarily for use by the log home industry (Green and others 2004; Green and others, in press). This study involved testing 233 logs of the Engelmann spruce (*Picea engelmannii*), alpine fir (*Abies lasiocarpa*), lodgepole pine species group (ES–AF–LP) in bending and compression parallel to the grain. These logs were machined to a constant diameter of 9 in. A static test on 170 logs showed that the relationship between MOR and MOE on these larger logs could be considered independent of species (Fig. 5, $R^2 = 0.68$). The study also found a predictable relationship between UCS and MOR (Fig. 6). A prototype machine was built for this project to determine the dynamic modulus of elasticity in Etv of a log based on its natural frequency of vibration (Murphy 2000). Compared with the visual grading, the proposed mechanical grading system gave higher yields for a specified set of allowable properties and could produce grades with allowable properties higher than could be justified by D 3957 procedures.

While the log home study was in progress, interest began to develop in using small-diameter logs as truss members and columns in engineered roundwood structures (Wolfe and Moseley 2000). The success of the proposed mechanical grading system for the 9-in.-diameter logs prompted extension of the research to smaller diameter logs. In the small-log studies, approximately 300 logs were selected for each of two species—suppressed growth Douglas-fir (*Pseudotsuga menziesii*) and plantation grown ponderosa pine (*Pinus ponderosa*). The logs were predominately 3 to 7 in. in diameter and mechanically debarked. Using Etv in the green condition, the logs for each species were separated into three groups that were "matched" in terms of the average value and the range of values. The logs were then air dried in Hayfork, California, to a moisture content of 15% to 20%. Two groups of logs were shipped to FPL and one to the University of Idaho. One of the two groups of tapered logs sent to FPL was tested in 1/3-point bending and the other in short-column compression parallel to the grain

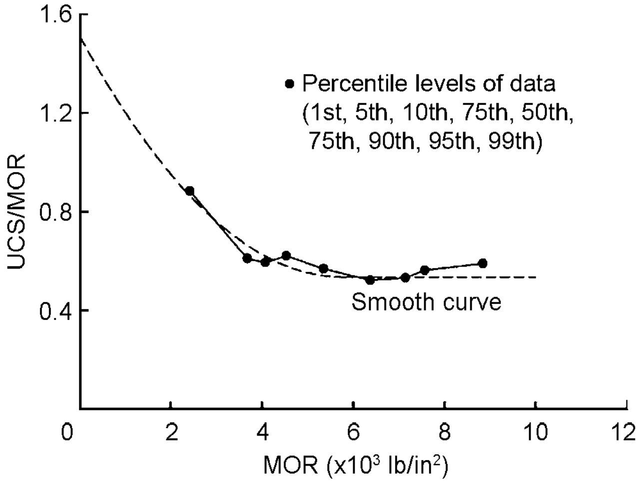

**Figure 6—Relationship between ultimate compression stress parallel to grain (UCS) and modulus of rupture (MOR) for 9-in.-diameter logs (Green and others, in preparation).**

**Table 2—Effect of machining to a constant diameter on the flexural properties of 3- to 6-in.-diameter Douglas-fir and ponderosa pine[a]**

| | | Tapered | | | Uniform | | | U/T (mean value) |
|---|---|---|---|---|---|---|---|---|
| Property | Species | Mean | 5th | 95th | Mean | 5th | 95th | |
| MOR ($\times 10^3$ lb/in$^2$) | Douglas-fir | 12.398 | 8.500 | 16.104 | 11.458 | 8.610 | 14.230 | 0.924 |
| | Ponderosa pine | 5.506 | 3.478 | 8.269 | 4.866 | 3.600 | 6.332 | 0.884 |
| MOE ($\times 10^6$ lb/in$^2$) | Douglas-fir | 2.327 | 1.720 | 2.971 | 1.981 | 1.474 | 2.466 | 0.851 |
| | Ponderosa pine | 1.128 | 0.710 | 1.520 | 0.756 | 0.386 | 1.101 | 0.670 |

[a] Green and others (in press), Gorman and others (in preparation).

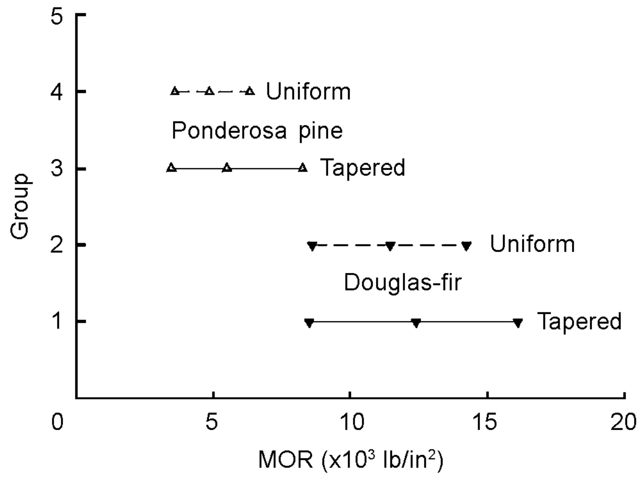

**Figure 7—Effect of log processing on the modulus of rupture (MOR) of 3- to 6-in.-diameter logs (5th percentile, mean, 95th percentile).**

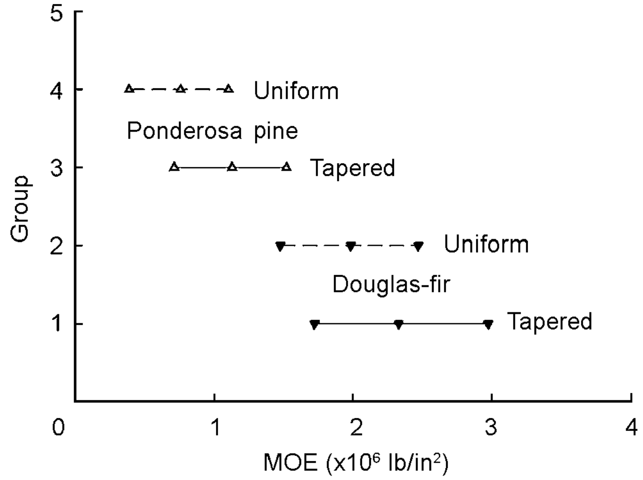

**Figure 8—Effect of log processing on the modulus of elasticity (MOE) of 3- to 6-in.-diameter logs (5th percentile, mean, 95th percentile).**

(Green and others, in preparation). The logs sent to the University of Idaho were machined to a constant (here referred to as "uniform") diameter and tested in 1/3-point bending (Gorman and others, in preparation). Pertinent results from both the small- and large-log studies for the proposed mechanical grading of the logs for two pedestrian bridges are summarized in the following section.

## Effect of Mechanical Processing on the Flexural Properties of Small-Diameter Logs

In general, machining small-diameter logs to a constant diameter removes much of the mature wood on the outside of the beam, thus exposing more of the juvenile wood core. It also tends to expose more knots, especially in species that readily self-prune limbs on the lower part of the stem as the tree grows. The net effect of the machining is to lower both MOR and MOE. For 3- to 6-in. suppressed-growth Douglas-fir logs, the MOR of logs machined to a uniform diameter was reduced by about 8%, whereas the MOE was reduced about 15% (Table 2). For 3- to 6-in. ponderosa pine logs, the MOR was reduced about 12% and the MOE about 33%. The greater effect of processing on the properties of ponderosa pine compared with those of Douglas-fir was probably a result of the respective ages of the trees, coupled with the relatively larger juvenile wood core of the shade-intolerant ponderosa pine. The suppressed-growth Douglas-fir trees had an average age of 67 years, whereas the average age of the ponderosa pine was only 42 years. The effect of processing on flexural properties is graphically shown in Figures 7 and 8. Note that the 95th percentile of the uniform diameter ponderosa pine logs MOE was slightly less than the mean value of the MOE of the tapered logs (Fig. 8).

Both the ponderosa pine and Douglas-fir logs machined to a constant diameter made the assigned $F_b$ values for the Unsawn visual grade, and Douglas-fir made the assigned MOE value (Gorman and others, in preparation). However, the high juvenile wood content of the logs caused logs tested in bending to fail suddenly with a brash-looking failure surface. For the Unsawn grade, the MOE of the ponderosa pine logs machined to a constant diameter was about 25% lower than the average assigned by D 3957 procedures. One advantage of mechanically grading small-diameter logs is that the MOE of each log is measured, rather than basing MOE on a visual grade.

### MOE–Etv

Table 3 summarizes regression relationships between MOE and Etv by log size, type of processing (tapered or uniform

**Table 3—Relationship between modulus of elasticity by static test (MOE) and modulus of elasticity by transverse vibration (Etv) for round timbers**

| | | | | | | $Y = A + BX$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| $Y$ | $X$ | Processing | Species[a] | Diameter (in.) | $N$ | $A$ | $B$ | $R^2$ | Reference[b] |
| MOE ($\times 10^6$ lb/in$^2$) | Etv ($\times 10^6$ lb/in$^2$) | Tapered | DF | 3 to 6 | 93 | 0.7704 | 0.7218 | 0.54 | 1 |
| | | | PP | | 97 | 0.1346 | 0.8770 | 0.66 | 1 |
| | | | DF+ PP | | 190 | –0.0376 | 1.0712 | 0.90 | 1 |
| | | Uniform | ES–AF–LP | 9 | 169 | 0.0038 | 0.9780 | 0.83 | 2 |
| | | | DF | 3 to 6 | 93 | 0.1636 | 0.8195 | 0.79 | 3 |
| | | | PP | | 100 | –0.0046 | 0.8878 | 0.83 | 3 |
| | | | DF+PP | | 193 | –0.0010 | 0.8908 | 0.97 | 3 |

[a] Douglas-fir, DF; ponderosa pine, PP; Engelmann spruce, ES; alpine fir, AF; lodgepole pine, LP.
[b] 1, Green and others (in preparation); 2, Green and others (2004); 3, Gorman and others (in preparation).

cross-section along the length of the log), and species (or species group). In all cases, the correlation is good to excellent. For small-diameter logs with taper, the MOE–Etv relationships for the two species are significantly different at the 0.001 probability level (highly significant). Visual inspection shows that both the slopes and intercepts are different (Fig. 9) because of the difference between the two species in percentage of juvenile wood in the log cross-section. Small-diameter logs machined to a uniform cross-section show no significant difference at the 0.05 probability level in the MOE–Etv relationship between the two species (Fig. 9 solid lines). For these machined logs, the percentage juvenile wood content is very high for both species. Thus, for small-diameter logs machined to a uniform diameter, it would be more conservative to use the MOE–Etv relationship for the combined Douglas-fir–ponderosa pine data (Table 3):

$$\text{MOE} = 0.891\text{Etv} - 0.001 \qquad (1)$$

Although not plotted in Figure 9, the MOE–Etv relationship for the 9-in.-diameter uniform logs appears to be a composite of the results for the Douglas-fir and ponderosa pine tapered logs (Table 3). This is probably because these logs were initially large enough that even with machining to a constant diameter, the juvenile wood had little effect on properties.

Figure 10 compares the results obtained on the 3- to 6-in. Douglas-fir and ponderosa pine logs with some limited unpublished data from the University of Idaho on tests of 44 lodgepole pine logs, which likely came from Canada. In the Idaho study, the logs were obtained from a pole manufacturer in northern Idaho and were dowelled in the green condition to a constant diameter of 3.5 in. The logs were then dried and conditioned in a relative humidity of 65% and tested in 1/3-point bending following ASTM D 198 procedures. The average moisture content of the logs was about 12%. Because the tests showed no statistical difference between the Douglas-fir and ponderosa pine, there would appear to be no difference in the MOE–Etv relationship between these species and the lodgepole pine. Thus we

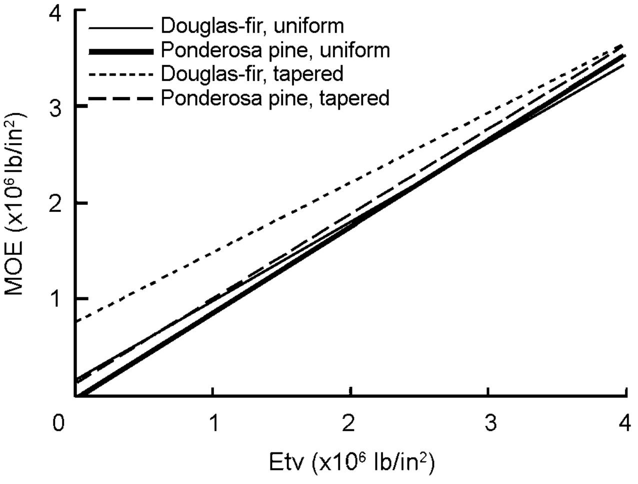

**Figure 9—Relationship between modulus of elasticity by static test (MOE) and modulus of elasticity by transverse vibration (Etv) for 3- to 6-in.-diameter logs (Green and others, in preparation; Gorman and others, in preparation).**

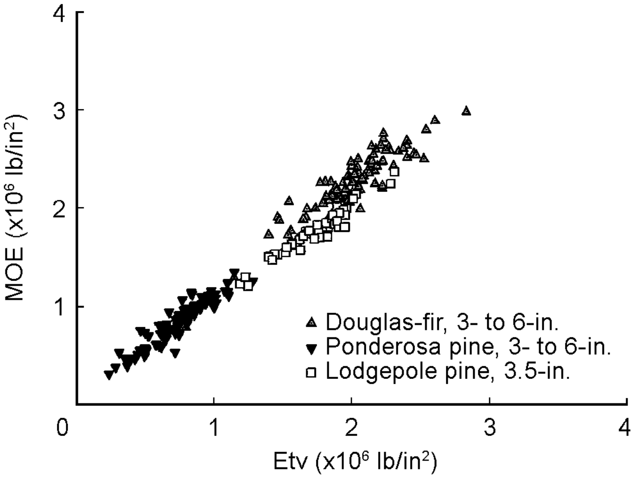

**Figure 10—Effect of species on the relationship between modulus of elasticity by static test (MOE) and modulus of elasticity by transverse vibration (Etv) for small-diameter logs machined to a constant cross section (Gorman and others, in preparation).**

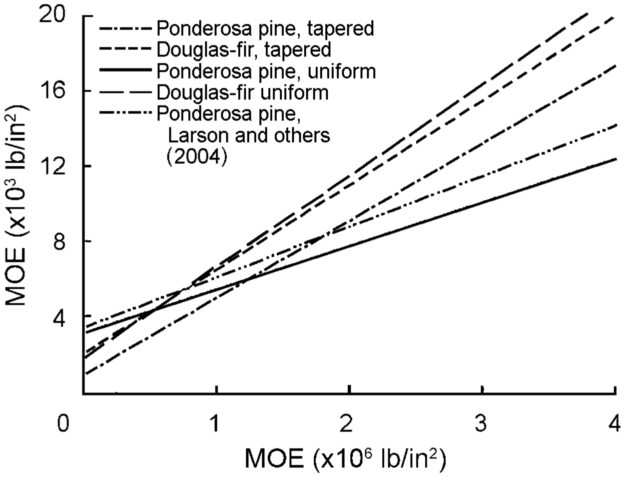

**Figure 11—Relationship between modulus of rupture (MOR) and modulus of elasticity (MOE) for small-diameter logs (Green and others, in preparation; Gorman and others, in preparation; Larson and others, in preparation).**

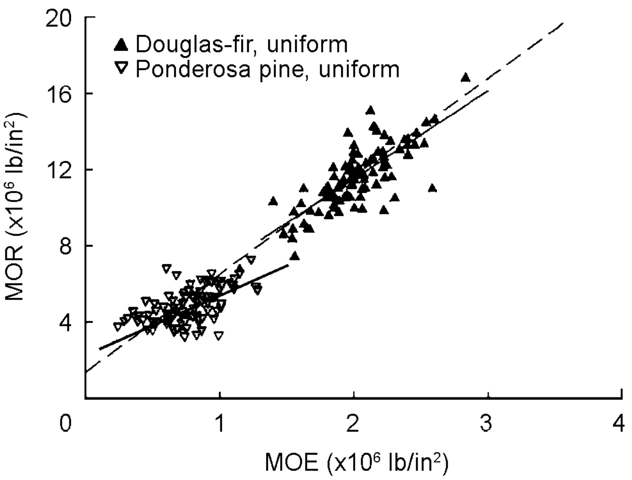

**Figure 12—Relationship between modulus of rupture (MOR) and modulus of elasticity by static test (MOE) for 3- to 6-in.-diameter logs machined to a constant cross section (Gorman and others, in preparation).**

conclude that Equation (1) should be used to predict the static MOE of the lodgepole pine logs for the two bridges.

## MOR–MOE

Table 4 summarizes regression relationships between MOR and MOE determined by static test, log size, type of processing, and species. With the exception of small-diameter ponderosa pine logs that have been machined to a uniform diameter, the relationships are generally good to excellent. The relationship for the uniform ponderosa pine logs is highly significant, even though the $R^2$ value is low. The lower value might be a peculiarity of this data set; however, Larson and others (2004) found $R^2 = 0.22$ in a study of 3- to 13-in. ponderosa pine logs. The MOE–MOR regression for the Larson study is reported only for the combination of uniform and tapered logs, and the data were adjusted to a moisture content of 12% using a procedure previously given in ASTM D 2915 for adjusting the MOE of 2- to 4-in.-thick dimension lumber. The regression equations between tapered and uniform diameter logs for the combined Douglas-fir and ponderosa pine logs show significant statistical difference at the 0.05 level of confidence. For Douglas-fir, the slopes are relatively the same for tapered and uniform logs, but for ponderosa pine they are not (Fig. 11). For MOE > $1.252 \times 10^6$ lb/in$^2$, the equation for uniform ponderosa pine provides the more conservative estimate of MOR,

$$\text{MOR} = 2.323 \times \text{MOE} + 3.110 \qquad (2)$$

whereas below this value the equation for tapered ponderosa pine is more conservative:

$$\text{MOR} = 4.125 \times \text{MOE} + 0.853 \qquad (3)$$

Although the MOE–MOR regression equations for the two species are statistically different for logs of uniform cross-section, there is room to debate the practical implementation of this relationship. Figure 12 shows the actual data plotted with both species on the same graph for logs of uniform cross section. Here the regression equations for each individual species and for the combined species data are

**Table 4—Relationship between modulus of elasticity by static test (MOE) and modulus of rupture by static test (MOR) round timbers**

| | | | | | | $Y = A + BX$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| $Y$ | $X$ | Processing | Species[a] | Diameter (in.) | $N$ | $A$ | $B$ | $R^2$ | Reference[b] |
| MOE (×10$^6$ lb/in$^2$) | MOR (×10$^6$ lb/in$^2$) | Tapered | DF | 3 to 6 | 92 | 1.961 | 4.513 | 0.58 | 1 |
| | | | PP | | 97 | 0.853 | 4.125 | 0.54 | 1 |
| | | | DF + PP | | 189 | –0.559 | 5.518 | 0.91 | 1 |
| | | Uniform | ES–AF–LP[a] | 9 | 169 | –1.340 | 5.586 | 0.68 | 2 |
| | | | DF | 3 to 6 | 102 | 1.766 | 4.865 | 0.71 | 3 |
| | | | PP | | 101 | 3.110 | 2.323 | 0.30 | 3 |
| | | | DF + PP | | 203 | 1.122 | 5.125 | 0.92 | 3 |

[a] Douglas-fir, DF; ponderosa pine, PP; Engelmann spruce, ES; alpine fir, AF; lodgepole pine, LP.

[b] 1, Green and others (in preparation); 2, Green and others (2004); 3, Gorman and others (in preparation).

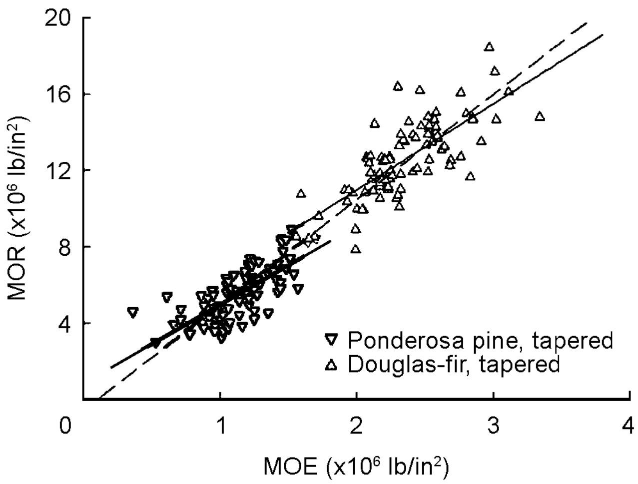

**Figure 13—Relationship between modulus of rupture (MOR) and modulus of elasticity by static test (MOE) for tapered 3- to 6-in.-diameter logs (Green and others, in preparation).**

shown. The influence of the lowest four pieces of ponderosa pine on the MOR–MOE regression is apparent. It would be easy to imagine one curve fitting both species. Figure 13 shows the same plot for tapered logs, in which the slopes of the regression equations for the individual species are closer. One regression equation could possibly fit both species, but again a few pieces of ponderosa pine with low MOE values lie above the regression equation and reduce the slope of the ponderosa pine equation. Figure 14 compares the limited data on the 44 3.5-in. uniform-diameter lodgepole pine logs with the 3- to 6-in. uniform-diameter logs. These limited data would suggest that an equation fit to both species for the 3- to 6-in.-diameter logs might be a better predictor of properties than would ponderosa pine data alone:

$$\text{MOR} = 5.125 \times \text{MOE} + 1.122 \quad (4)$$

## UCS–MOR

Green and others (in preparation) investigated the relationship between UCS and bending strength for dry 3- to 6-in. Douglas-fir and ponderosa pine logs. The logs all came from Shasta–Trinity National Forest in northern California. The logs were debarked (therefore tapered) and matched by Etv in the green condition to provide data sets of equal estimated quality. Ninety nine logs of each species were tested in bending, and 87 Douglas-fir logs and 99 ponderosa pine logs were tested in compression following procedures of ASTM D 198. A plot of the UCS/MOR relationship by position in the strength distribution (percentile level) shows the expected curvilinear relationship between the UCS/MOR ratio and MOR (Fig. 15). The average trend in the relationship is given:

$$\text{UCS/MOR} = 0.00704(\text{MOR})^2 - 0.1130(\text{MOR}) + 0.853 \quad (5)$$

for MOR ≤ $8.018 \times 10^3$ lb/in$^2$ and UCS/MOR = 0.400 for MOR > $8.018 \times 10^3$ lb/in$^2$.

Also as expected (Green and others 2004), the relationship for the 3- to 6-in.-diameter logs yields a lower UCS/MOR ratio for a given MOR value than the relationship previously found for 9-in.-diameter logs. When the small-diameter logs are classified into diameter groupings based on the average diameter at the middle of the log, the ratio is also seen to vary somewhat by diameter (Fig. 16). A more conservative estimate for the UCS/MOR relationship could be obtained by adjusting Equation (5) downward:

$$\text{UCS/MOR} = 0.00704(\text{MOR})^2 - 0.1130(\text{MOR}) + 0.750 \quad (6)$$

for MOR ≤ $8.018 \times 10^3$ lb/in$^2$ and UCS/MOR = 0.30 for MOR > $8.018 \times 10^3$ lb/in$^2$.

Machining small-diameter logs to a constant diameter lowers flexural properties and the MOR–MOE relationship. Because no data are available on the UCS/MOR relationship for small-diameter lodgepole pine logs machined to a constant diameter, we recommend that the more conservative UCS/MOR relationship given in Equation (6) be used to estimate $F_{c||}$ for the lodgepole pine logs tested in this study.

## UTS–MOR

Currently, the allowable tensile strength parallel to the grain ($F_t$) of round timbers is estimated as $0.55F_b$ (ASTM D 3957). This is an average value given in ASTM D 245 and is based on tests of 2-in.-thick dimension lumber. Direct evidence to support the use of the 0.55 ratio for logs is lacking. ASTM D 1990 for visually graded lumber and D 6570 for mechanically graded lumber use a more conservative ratio of 0.45 if no collaborative data support a higher ratio. Green

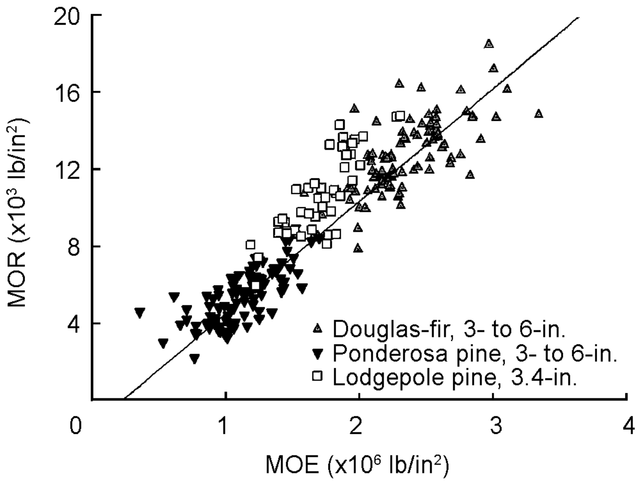

**Figure 14—Effect of species on the relationship between modulus of rupture (MOR) and modulus of elasticity (MOE) by static test for small-diameter logs machined to a constant cross-section (Gorman and others, in preparation).**

and others (in preparation) reviewed the limited available data on the tensile strength of round timbers. The following information is summarized from their discussion.

Pellerin and others (1987) tested 81 lodgepole pine logs in tension parallel to the grain following procedures of ASTM D 198. The logs were sampled from throughout the growth range of interior lodgepole pine. The logs were approximately 3 in. (76 mm) in diameter after debarking and were at about 13% moisture content at time of test. To overcome the problems of crushing in the special grips developed for the study, the center portion of each stem was necked down to approximately 2.25 in. prior to loading. Mean tensile strengths for these logs are not reported in Pellerin and others (1987); however, the mean value is given in Koch (1996). The UTS values range from 4,060 lb/in$^2$ for logs sampled at 42.5° latitude to 5,680 lb/in$^2$ for those sampled at 60° latitude. The overall mean value was 5,158 lb/in$^2$.

The mean MOR value for the 44 lodgepole pine logs from the unpublished University of Idaho data was 10,803 lb/in$^2$. Using the mean values for these logs and the mean UTS value from Pellerin and others (1987) gives a UTS–MOR ratio of 0.48. Although recognizing the limitations of the available data, we recommend using the UTS–MOR ratio of 0.45 given in ASTM D 4761 for determining allowable properties for a given mechanical grade. This ratio might provide safer estimates of $F_\mathrm{t}$ than the ratio of 0.55 specified in D 3957/D 245 for small-diameter logs, especially those machined to a constant cross section.

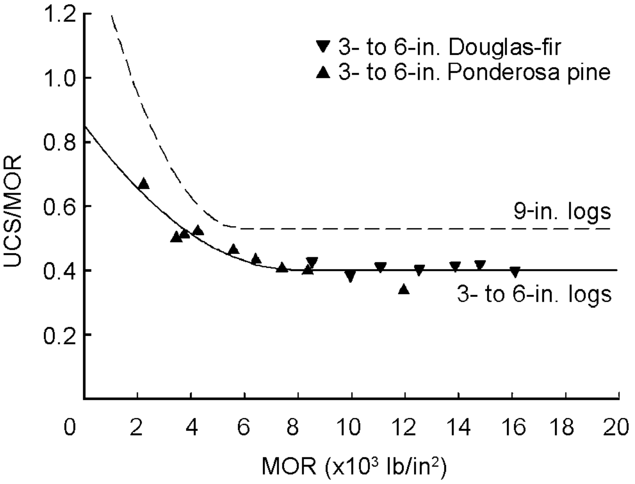

**Figure 15—Relationship between ultimate compression stress parallel to the grain (UCS) and modulus of rupture (MOR) for 3- to 6-in.-diameter logs (Green and others, in press) (solid line, mean trend for this study; dotted line, mean trend for 9-in.-diameter logs from Green and others, in preparation).**

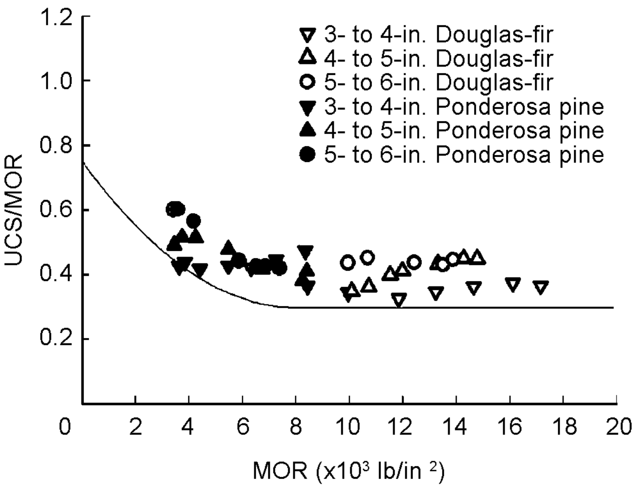

**Figure 16—Effect of log diameter class on relationship between ultimate compression stress parallel to the grain (UCS) and modulus of rupture (MOR) for small-diameter logs at approximately 14% moisture content (conservative relationship fit to the data).**

### Allowable Shear Strength ($F_\mathrm{v}$) and Compression Strength Perpendicular to the Grain ($F_{\mathrm{c}\perp}$)

Allowable shear strength ($F_\mathrm{v}$) and allowable compression strength perpendicular to the grain ($F_{\mathrm{c}\perp}$) are determined from tests of clear wood and do not vary with visual grade (ASTM D 3957). Thus, we recommend that the $F_\mathrm{v}$ and $F_{\mathrm{c}\perp}$ values assigned to visually graded lodgepole pine logs be used for mechanically graded round timbers. This recommendation is consistent with the recommended practice for mechanically graded dimension lumber (ASTM D 6570).

# Methods

## Material

The superstructure of both bridges will be constructed primarily of lodgepole pine salvaged from beetle-killed trees cut on private property near Elk City, Idaho. After harvest, the logs were transported to Porterbuilt, Inc., near Hamilton, Montana. There the logs were machined to a constant diameter of approximately 6 in. and cut to various lengths from 12 to 20 ft, as specified by Beaudette Engineering. The logs were graded as No.1, 2, or 3 by a quality supervisor of Timber Products Inspection, Inc. Because of an oversight, the Unsawn grade was not separated from the No. 1 grade logs.

## Procedures

Immediately prior to testing, the moisture content of about five logs of each of the various log length groupings was obtained using a Delmhorst model J-2000 electrical resistance moisture meter (Delmhorst Instrument Company, Towaco, New Jersey) using an insulated two-prong probe driven to a depth of about 2 in. Air temperature at time of test was generally from 75°F to 90°F.

**Figure 17—Determination of modulus of elasticity by transverse vibration of lodgepole pine logs at Portbuilt, Inc., Hamilton, Montana, in July 2004.**

The MOE of the logs in transverse vibration was determined on all the candidate logs in the log yard of Porterbuilt, Inc., in Hamilton, Montana (Fig. 17) (Murphy 2000; Murphy, in press). The logs were supported full length, with the span being approximately 4 in. shorter than the log's length. Log lengths, log spans, and log circumferences were determined for all logs. The FPL prototype machine determines the weight and frequency of vibration from load cells on each end of the log. This information is used to determine the average Etv of the log.

Mechanical grades for the logs were determined using procedures developed in previous studies on the mechanical grading of round timbers (Green and others 2004; Green and others, in preparation). The exact procedures are discussed and examples provided in the Results section under Mechanical Grading. In general, we followed established procedures for Machine Stress Rated (MSR) lumber (Galligan and McDonald 2000), a specific process, as opposed to "mechanical grading." In the MSR process, the MOE is limited to a coefficient of variation (COV) of 11% on the lower tail of the stiffness distribution. Other types of mechanically graded lumber are produced commercially, some of which allow a user-specified COV. A good discussion of mechanical grading for softwood dimension lumber is given in Smulski (1997). The mechanical grading procedure used here has been used successfully in a number of FPL studies on softwood and hardwood dimension lumber and rectangular timbers. Although it addresses softwood dimension lumber, a good discussion of some marketing considerations in the production of MSR lumber may be found in appendix B of Green and others (2000).

**Table 5—Grade yield and grade-controlling characteristic for visually graded 6-in.-diameter lodgepole pine logs**

| | Log grade[a] | | | |
|---|---|---|---|---|
| Characteristic | No. 1 | No. 2 | No. 3 | Cull |
| Number of logs | 188 | 21 | 27 | 56 |
| Knots | | 8 | 2 | 36 |
| Slope of grain | | 12 | 13 | 1 |
| Splits | | | 3 | 2 |
| Unsound wood | | | 3 | 3 |
| Break | | | | 2 |
| Insect damage | | | | 3 |
| Saw cut | | | | 1 |
| Shake | | | 3 | 3 |
| Wane | | | | 2 |
| Under size | | | | 1 |
| Check | | | 1 | |
| Not specified, or not recorded | 188[b] | 1 | 2 | 2 |

[a] TP (1995).

[b] No defect specified, as is typical industry practice for the highest grade determined.

# Results

## Visual Grading

The average moisture content of the 30 logs sampled was 19.3%, with a range from 12% to 24%. The diameter of the logs was constant at about 6-1/8 in.

The visual grades of the 292 logs used in this study are given in Table 5. All were lodgepole pine except one (log no. 594), which was identified by the TP grader as Engelmann spruce. This log was retained in the data set and is included in all subsequent discussion. Additional information on the individual logs is given in Appendixes A and B. About 64% of the logs made No. 1 grade, with less than 10% each in No. 2 and 3 grades. Probably a high percentage of the No. 1 logs would have qualified for the Unsawn grade, but as noted previously, this grade was not identified separately. More than 19% of the logs failed to make No. 3 grade and were considered culls. Of these logs, by far the largest cause for downgrade was excessive knot size, which characterized 64% of the 56 cull logs. As is common industry practice for the highest grade, no limiting characteristic was recorded for the No.1 grade logs. Slope of grain was the most prevalent limiting characteristic for the No. 2 and 3 grade logs. The higher occurrence of unsound wood and insect damage in the No. 3 and cull logs is a reflection of using logs cut from salvaged (dead) trees.

## Mechanical Grading

Only the 236 logs that made at least a No. 3 visual grade were considered for mechanical grading. All subsequent discussion pertains only to these logs.

### Modulus of Elasticity

The Etv values measured on the logs averaged 1.639 × $10^6$ lb/in$^2$, with a range from 1.002 to 2.633 × $10^6$ lb/in$^2$ (Table 6). The static MOE values were estimated from the combined ponderosa pine–Douglas-fir data sets for logs

**Table 6—Measured values of modulus of elasticity by transverse vibration (Etv) and estimated[a] values by static test (MOE) for 236 lodgepole pine logs**

| Property ($10^6$ lb/in$^2$) | Mean | Percentile level 5th | 10th | 25th | 50th | 75th | 90th | 95th |
|---|---|---|---|---|---|---|---|---|
| Etv | 1.638 | 1.237 | 1.310 | 1.446 | 1.608 | 1.822 | 2.008 | 2.086 |
| MOE[a] | 1.459 | 1.102 | 1.167 | 1.288 | 1.433 | 1.623 | 1.789 | 1.859 |

[a] MOE estimated from combined data on 3- to 6-in. ponderosa pine and Douglas-fir logs machined to a constant diameter (Eq. (1), page***).

machined to a constant diameter (Eq. (1)). The MOE values averaged $1.460 \times 10^6$ lb/in$^2$, with a range 0.893 to $2.460 \times 10^6$ lb/in$^2$ (Table 6).

## Assignment of Mechanical Grades

As discussed previously, mechanical grades were determined from the estimated static MOE values. For the assigned MOE of mechanically graded logs to qualify for a grade, two criteria must be met:

1. The minimum MOE accepted into the grade must be 0.82 times the target average MOE of the grade.
2. The actual MOE of all pieces that meet the first criteria must be at least as high as the target average MOE of the grade.

Criterion 1 establishes the "5th percentile MOE" and ensures the traditional 11% COV on the lower-tail MOE for mechanically graded lumber. As an example, first consider that only one MSR grade with an MOE of $1.4 \times 10^6$ lb/in$^2$ will be produced. On the basis of the first criterion, 215 of 236 lodgepole pine logs for the bridge project potentially qualified for a mechanical grade (see Table 6 and worksheet in Appendix A). The average MOE of these 215 logs is $1.497 \times 10^6$ lb/in$^2$, thus criterion 2 is satisfied, and all the 215 logs may be assigned a grade of "1.4E."

As another example, assume that two MSR grades are desired. First, let's target an average MOE of $1.9 \times 10^6$ lb/in$^2$ for the upper grade. With criterion 1, all logs with an MOE at least as high as $0.82 \times 1.9 = 1.558$ are candidates. Seventy one logs meet criterion 1 (Appendix A). However, the average MOE of these logs is only $1.748 \times 10^6$ lb/in$^2$. So to raise the average MOE to at least $1.9 \times 10^6$ lb/in$^2$, it is necessary to throw out logs with the lowest MOE values. When sufficient logs are eliminated, 26 logs meet criterion 2 and can be assigned a grade of "1.9E." The remaining 210 logs can now be considered for a lower grade. Average MOE of the remaining logs is $1.404 \times 10^6$ lb/in$^2$, so we first consider how many of the logs might qualify for a 1.4E grade. Applying the two criteria to these remaining logs, the minimum MOE must be $0.82 \times 1.4 = 1.148 \times 10^6$ lb/in$^2$. One hundred eighty nine of the 292 logs meet criterion 1, and the average MOE of these logs is $1.441 \times 10^6$ lb/in$^2$. Thus, all 189 logs may be assigned 1.4E. The remaining 21 No.1, 2, and 3 logs have visual grades with assigned properties below the mechanical grade for which they failed to qualify. Thus, these logs can retain their assigned allowable properties for the visual grades (Table 6).

The allowable bending strength ($F_b$) is determined from the assumed regression equation between MOR and MOE. When comparing the equations for ponderosa pine, we noted that the equation based on tapered samples (Eq. (3)) was

**Table 7—Grade yields from mechanically graded 6-in.-diameter lodgepole pine logs as predicted using Equation (7), page 12, for ponderosa pine**

| Option | MSR[a] grade | Pieces of MSR | Pieces from visual falldowns No. 1 | No. 2 | No. 3 | Cull | Total pieces |
|---|---|---|---|---|---|---|---|
| 1 | 1.9E-2600Fb | 26 | — | — | — | — | — |
|  | 1.4E-2150Fb | 189 | 16 | 2 | 3 | 56 | 292 |
| 2 | 1.8E-2500Fb | 49 | — | — | — | — | — |
|  | 1.3E-2050Fb | 183 | 1 | 1 | 2 | 56 | 292 |
| 3 | 1.7E-2450Fb | 88 | — | — | — | — | — |
|  | 1.3E-2050Fb | 144 | 1 | 1 | 2 | 56 | 292 |
| 4 | 1.6E-2350Fb | 147 | — | — | — | — | — |
|  | 1.2E-1950Fb | 86 | 1 | 1 | 1 | 56 | 292 |
| 5 | 1.5E-2250Fb | 196 | — | — | — | — | — |
|  | 1.1E-1900Fb | 39 | — | 1 | — | 56 | 292 |
| 6 | 1.4E-2150Fb | 215 | 16 | 2 | 3 | 56 | 292 |
| 7 | 1.3E-2050Fb | 232 | 1 | 1 | 2 | 56 | 292 |
| 8 | 1.2E-1950Fb | 233 | 1 | 1 | 1 | 56 | 292 |
| 9 | 1.1E-1900Fb | 235 | — | 1 | — | 56 | 292 |

[a]Machine Stress Rated.

**Table 8—Grade yields from mechanically graded 6-in.-diameter lodgepole pine logs as predicted using Equation (8), page 12, for the combined Douglas-fir and ponderosa pine data**

| Option | MSR[a] grade | Pieces of MSR | Pieces from visual falldowns | | | | Total pieces |
|---|---|---|---|---|---|---|---|
| | | | No. 1 | No. 2 | No. 3 | Cull | |
| 1 | 1.9E-3500Fb | 26 | — | — | — | — | — |
| | 1.4E-2250Fb | 189 | 16 | 2 | 3 | 56 | 292 |
| 2 | 1.8E-3350Fb | 49 | — | — | — | — | — |
| | 1.3E-2350Fb | 183 | 1 | 1 | 2 | 56 | 292 |
| 3 | 1.7E-3150Fb | 88 | — | — | — | — | — |
| | 1.3E-2350Fb | 144 | 1 | 1 | 2 | 56 | 292 |
| 4 | 1.6E-2950Fb | 147 | — | — | — | — | — |
| | 1.2E-2150Fb | 86 | 1 | 1 | 1 | 56 | 292 |
| 5 | 1.5E-2750Fb | 196 | — | — | — | — | — |
| | 1.1E-1950Fb | 39 | — | 1 | — | 56 | 292 |
| 6 | 1.4E-2550Fb | 215 | 16 | 2 | 3 | 56 | 292 |
| 7 | 1.3E-2350Fb | 232 | 1 | 1 | 2 | 56 | 292 |
| 8 | 1.2E-2150Fb | 233 | 1 | 1 | 1 | 56 | 292 |
| 9 | 1.1E-1950Fb | 235 | — | 1 | — | 56 | 292 |

[a] MSR, Machine Stress Rated.

**Table 9—Design values for mechanically graded 6-in.-diameter lodgepole pine logs developed using Equation (7), page 12, for ponderosa pine**

| Grade | Design values | | | | | |
|---|---|---|---|---|---|---|
| | $F_b$ (lb/in$^2$) | $F_t$ (lb/in$^2$) | $F_v$ (lb/in$^2$) | $F_{c\perp}$ (lb/in$^2$) | $F_{c\parallel}$ (lb/in$^2$) | MOE ($\times 10^6$ lb/in$^2$) |
| 1.9E | 2,600 | 1,150 | 95 | 395 | 975 | 1.9 |
| 1.8E | 2,500 | 1,150 | 95 | 395 | 975 | 1.8 |
| 1.7E | 2,450 | 1,100 | 95 | 395 | 950 | 1.7 |
| 1.6E | 2,350 | 1,050 | 95 | 395 | 950 | 1.6 |
| 1.5E | 2,250 | 1,000 | 95 | 395 | 925 | 1.5 |
| 1.4E | 2,150 | 950 | 95 | 395 | 900 | 1.4 |
| 1.3E | 2,050 | 925 | 95 | 395 | 900 | 1.3 |
| 1.2E | 1,950 | 875 | 95 | 395 | 875 | 1.2 |
| 1.1E | 1,900 | 850 | 95 | 395 | 850 | 1.1 |
| Visual grades[a] | | | | | | |
| No. 1 | 1,250 | 675 | 95 | 395 | 625 | 1.1 |
| No. 2 | 1,050 | 575 | 95 | 395 | 525 | 1.1 |
| No. 3 | 600 | 325 | 95 | 395 | 300 | 0.9 |

[a] TP (1995).

more conservative for MOE values below $1.25 \times 10^6$ lb/in$^2$, whereas the equation for uniform diameter logs (Eq. (2)) was more conservative for higher MOE values. Because most of the predicted MOE values for the lodgepole pine logs are above $1.25 \times 10^6$ lb/in$^2$ (Table 6), Equation (2) seems a better choice. At an MOE of $1.0 \times 10^6$ lb/in$^2$, Equation (2) predicts MOR that is about 9% higher than that predicted by Equation (3), and with an MOE of $1.1 \times 10^6$ lb/in$^2$, the difference is about 5% too high. For all higher MOEs, the MOR predicted by Equation (2) would be lower than those predicted by Equation (3). Whether to use Equation (2), which is just for uniform diameter ponderosa pine, or Equation (4), which is based on the combined species with uniform cross-section, is more arbitrary. Whereas we tend to think Equation (2) is better given the lack of knowledge on small-diameter ponderosa pine, both will be used to allow comparison of predicted properties.

First, we use the ponderosa pine data of Equation (2) as a basis for predicting MOR. Here we fit a 90% lower confidence interval on the regression equation on ponderosa pine machined to a constant diameter of 3 to 6 in. This provides an equivalent to the traditional 5th percentile used for visually graded lumber because it excludes 5% of the data on the lower side of the mean regression line. The equation is

$$\mathrm{MOR}_{0.05} = 2.323 \times \mathrm{MOE} + 1.850 \qquad (7)$$

For a 1.4E grade, the required minimum MOE value of 1.148 is used in Equation (7). Thus the estimated MOR value would be $2.323 \times 1.148 + 1.850 = 4.517 \times 10^3$ lb/in$^2$, or 4,517 lb/in$^2$ (App. A). This estimated 5th percentile would be divided by 2.1 (the general adjustment factor of ASTM D 245/D 6570) to give 2,151 lb/in$^2$. When rounded according to ASTM procedures, the assigned $F_b$ value would be 2,150. Thus, these logs would qualify as a 1.4E-2150Fb grade.

Table 7 presents the results for nine sorting options for producing mechanical grades from the 228 lodgepole pine logs using Equation (7) to predict MOR. The option chosen in practice depends upon the material requirements of the bridges. Grade assignments for individual logs using option 1 (two mechanical grades, 1.9E and 1.4E) are shown in Appendix B.

If the combined Douglas-fir and ponderosa pine data of Equation (4) are used to predict MOR, the 90% lower confidence interval is

$$MOR_{0.05} = 5.125 \times MOE - 0.532 \qquad (8)$$

Table 8 gives grades for the same MOE combinations used in Table 7. As expected, the $F_b$ value is higher using Equation (8) than if Equation (7) is used.

### Assignment of Other Allowable Properties

Other allowable properties may be assigned for each of the grade options. As previously discussed, $F_c$ is estimated from Equation (6). The recommended $F_t$ value is obtained as $0.45 \times F_b$. Allowable shear strength ($F_v$) and allowable strength in compression perpendicular to the grain ($F_{c\perp}$) do not vary by grade, so these values remain those assigned to lodgepole pine by Timber Products (TP 1995). Table 9 gives the design values predicted on the basis of Table 6 $F_b$ values (Eq. (7)) for MOR–MOE based only on ponderosa pine) and Table 10 gives them based on Table 8 $F_b$ values (Eq. (8)) for MOR–MOE based on the combined Douglas-fir and ponderosa pine data). The design values for visual grades are given in both tables for comparison.

## Recommendations

Two options are presented for determination of the allowable bending strength $F_b$ for the lodgepole pine logs that were mechanically graded in this study. Option 1 is based on the MOR–MOE relationship for 3- to 6-in.-diameter ponderosa pine logs machined to a constant diameter (Eq. (7), Tables 6 and 9). Given that there are few data on the MOR–MOE relationship for small-diameter lodgepole pine logs machined to a constant diameter, option 1 provides our preferred set of allowable properties. For a mechanical grade assigned an MOE = $1.4 \times 10^6$ lb/in$^2$, option 1 provides a 27% increase in MOE and a 72% increase in $F_b$ compared with a No. 1 visual grade. Property assignments under option 1 are more conservative than under option 2.

Option 2 is based on the MOR–MOE relationship fit to the combined ponderosa pine and Douglas-fir data for 3- to 6-in.-diameter logs machined to a constant diameter (Eq. (8), Tables 8 and 10). Statistics show that the MOR–MOE regression equations fit to the individual species are not the same (the difference is highly significant at the 0.001 probability level). However, limited data on 44 lodgepole pine logs machined to a constant diameter of approximately 3-3/8 in. appear to support the concept that the MOE–MOR relationship is virtually independent of species. This observation, plus previous results for logs of three species machined to a constant diameter of 9 in., suggests that a regression fit to the combined data set would provide more realistic design values. Therefore, we feel that option 2 is also technically valid. A further study on lodgepole pine logs was already contemplated prior to the initiation of this project and should provide definitive conclusions on the effect of species on the MOE–MOR relationship for small-diameter logs. For a $1.4 \times 10^6$ lb/in$^2$ MOE grade, the increase in $F_b$ is 80% larger than that assigned to a No. 1 visual grade.

**Table 10—Design values for mechanically graded 6-in.-diameter lodgepole pine logs developed using Equation (8), page 12, for the combined Douglas-fir and ponderosa pine data**

| | Design values | | | | | |
|---|---|---|---|---|---|---|
| Grade | $F_b$ (lb/in$^2$) | $F_t$ (lb/in$^2$) | $F_v$ (lb/in$^2$) | $F_{c\perp}$ (lb/in$^2$) | $F_{c\parallel}$ (lb/in$^2$) | MOE ($\times10^6$ lb/in$^2$) |
| 1.9E | 3,550 | 1,600 | 95 | 395 | 1,150 | 1.9 |
| 1.8E | 3,350 | 1,500 | 95 | 395 | 1,100 | 1.8 |
| 1.7E | 3,150 | 1,400 | 95 | 395 | 1,100 | 1.7 |
| 1.6E | 2,950 | 1,350 | 95 | 395 | 1,050 | 1.6 |
| 1.5E | 2,750 | 1,250 | 95 | 395 | 1,000 | 1.5 |
| 1.4E | 2,550 | 1,150 | 95 | 395 | 1,000 | 1.4 |
| 1.3E | 2,350 | 1,050 | 95 | 395 | 950 | 1.3 |
| 1.2E | 2,150 | 975 | 95 | 395 | 900 | 1.2 |
| 1.1E | 1,950 | 875 | 95 | 395 | 875 | 1.1 |
| Visual grades[a] | | | | | | |
| No. 1 | 1,250 | 675 | 95 | 395 | 625 | 1.1 |
| No. 2 | 1,050 | 575 | 95 | 395 | 525 | 1.1 |
| No. 3 | 600 | 325 | 95 | 395 | 300 | 0.9 |

[a] TP (1995).

The approach taken in this paper is to recommend property assignment procedures consistent with historical practices for assigning allowable properties to groups of logs sorted into visual or mechanical grades. We do not recommend that the equations presented in this paper be used to assign separate strength values to individual logs. Such a practice would not be consistent with historical assumptions about factors of safety for structural lumber products.

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# Appendix A—Mechanical Grading Worksheet

**Mechanical grading worksheet using Equation (7) for MOR–MOE relationship for only ponderosa pine machined to a constant diameter. $\text{MOR}_{0.90lcl}$ = 2.323(0.902) + 1.850 = 3.945 × $10^3$ lb/in$^2$ (Eq. (7), page 12)**

| | Mechanical Grade | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1.1E | 1.2E | 1.3E | 1.4E | 1.5E | 1.6E | 1.7E | 1.8E | 1.9E |
| **Mean modulus of elasticity of 1st mechanical grade[a]** | | | | | | | | | |
| Min E=0.82$E_1$ | 0.902 | 0.984 | 1.066 | 1.148 | 1.230 | 1.312 | 1.394 | 1.476 | 1.558 |
| N$\geq$0.82$E_1$ | 235/292 | 233/292 | 232/292 | 215/292 | 196/292 | 168/292 | 136/292 | 101/292 | 71/292 |
| % Yield | 80.5 | 79.8 | 79.5 | 74.6 | 67.1 | 57.5 | 46.6 | 34.6 | 24.3 |
| Mean $E_1$ | 1.462 | 1.466 | 1.468 | 1.497 | 1.525 | 1.567[e] | 1.618[e] | 1.680[e] | 1.748[e] |
| New min E | | | | | | 1.370[f] | 1.510 | 1.650 | 1.780 |
| N @ Adj $E_1$ | | | | | | 147/292 | 88/292 | 49/292 | 26/292 |
| New min $E_1$ | | | | | | 1.600 | 1.707 | 1.810 | 1.903 |
| Adjusted percentage yield | | | | | | 50.3 | 30.1 | 16.8 | 8.9 |
| **Mean modulus of elasticity of 2nd mechanical grade if target E $\geq$1.1E[b]** | | | | | | | | | |
| Mean E of $E_1$ rejects | 0.893 | 0.918 | 0.946 | 1.076 | 1.135 | 1.227 | 1.312 | 1.367 | 1.404 |
| Target MOE of 2nd Grade | | | | | 1.1 | 1.2 | 1.3 | 1.3 | 1.4 |
| Min E=0.82$E_2$ | | | | | 0.902 | 0.984 | 1.066 | 1.066 | 1.148 |
| N$\geq$0.82$E_2$ | | | | | 39/292 | 86/292 | 144/292 | 183/292 | 189/292 |
| Mean $E_2$ | | | | | 1.141 | 1.237 | 1.322 | 1.376 | 1.439 |
| % yield $E_2$ | | | | | 13.4 | 29.5 | 49.3 | 62.7 | 64.7 |
| % yield of visual grades[d] | 0 | 0 | 0 | 0 | 0.3<br>(1/292) | 1.0<br>(3/292) | 1.4<br>(4/292) | 1.4<br>(4/292) | 7.2<br>(21/292) |
| % yield of < No. 3 visual | 19.2 | 19.2 | 19.2 | 19.2 | 19.2 | 19.2 | 19.2 | 19.2 | 19.2 |
| **Estimated $F_b$ of mechanical grade $E_1$[c]** | | | | | | | | | |
| MOR | 3,945[4] | 4,136 | 4,326 | 4,517 | 4,707 | 4,898 | 5,088 | 5,279 | 5,469 |
| MOR/2.1 | 1,879 | 1,969 | 2,060 | 2,151 | 2,241 | 2,332 | 2,423 | 2,514 | 2,604 |
| $F_b$ | 1,900 | 1,950 | 2,050 | 2,150 | 2,250 | 2,350 | 2,450 | 2,500 | 2,600 |

[a] Sample size of 292 includes 56 pieces that did not make No. 3 visual grade.

[b] Second, lower, grade not considered unless mean E at least 1.1 x $10^3$ lb/in$^2$.

[c] $F_b$ estimated from Equation (7) for uniform diameter ponderosa pine logs/2.1.

[d] Pieces not making mechanical grade, but with visual grade of No. 1, 2, or 3.

[e] Mean E value of sorted logs is less than target average grade E. Must raise minimum value of 0.82E and recalculate.

[f] Obtained by dropping off remaining pieces with lowest MOE values until required average MOE is achieved.

# Appendix B–Grade Assignments for Individual Logs

**Grade assignments for individual logs using option 1 (two mechanical grades, 1.9E and 1.4E)**

| Log number | MSR grade | Visual grade | MOE ($\times10^6$ lb/in$^2$) | Length (ft) |
|---|---|---|---|---|
| 391 | No. 1 | No. 1 | 0.947 | 16.71 |
| 392 | No. 1 | No. 1 | 1.114 | 16.63 |
| 393 | Cull | Cull | — | 16.81 |
| 394 | 1.4E | No. 2 | 1.169 | 16.58 |
| 395 | 1.4E | No. 1 | 1.426 | 16.73 |
| 396 | No. 1 | No. 1 | 1.093 | 16.69 |
| 397 | 1.4E | No. 1 | 1.225 | 16.67 |
| 398 | 1.4E | No. 1 | 1.553 | 16.71 |
| 399 | 1.4E | No. 1 | 1.351 | 16.67 |
| 400 | 1.4E | No. 1 | 1.585 | 18.73 |
| 401 | 1.4E | No. 1 | 1.640 | 19.00 |
| 402 | 1.4E | No. 3 | 1.476 | 18.83 |
| 403 | 1.4E | No. 1 | 1.633 | 18.29 |
| 404 | 1.4E | No. 1 | 1.308 | 19.23 |
| 405 | 1.4E | No. 1 | 1.627 | 18.69 |
| 406 | 1.4E | No. 3 | 1.375 | 18.42 |
| 407 | 1.4E | No. 3 | 1.632 | 18.90 |
| 408 | 1.4E | No. 1 | 1.769 | 18.48 |
| 409 | 1.4E | No. 1 | 1.647 | 19.04 |
| 410 | 1.4E | No. 1 | 1.662 | 18.77 |
| 411 | 1.4E | No. 1 | 1.564 | 18.04 |
| 412 | 1.9E | No. 1 | 1.897 | 17.81 |
| 413 | Cull | Cull | — | 18.40 |
| 414 | 1.4E | No. 1 | 1.772 | 18.79 |
| 415 | No. 1 | No. 1 | 1.101 | 17.60 |
| 416 | Cull | Cull | — | 18.06 |
| 417 | 1.4E | No. 1 | 1.630 | 18.71 |
| 418 | 1.4E | No. 3 | 1.457 | 18.46 |
| 419 | 1.4E | No. 1 | 1.474 | 19.02 |
| 420 | 1.4E | No. 1 | 1.719 | 18.79 |
| 421 | 1.4E | No. 1 | 1.507 | 18.63 |
| 422 | 1.4E | No. 1 | 1.245 | 12.75 |
| 423 | 1.4E | No. 1 | 1.502 | 12.67 |
| 424 | 1.4E | No. 1 | 1.473 | 12.67 |
| 425 | No. 1 | No. 1 | 1.103 | 13.65 |
| 426 | 1.4E | No. 1 | 1.198 | 12.63 |
| 427 | Cull | Cull | — | 12.69 |
| 428 | 1.4E | No. 1 | 1.423 | 12.69 |
| 429 | 1.4E | No. 1 | 1.696 | 12.25 |
| 430 | 1.4E | No. 1 | 1.329 | 13.00 |
| 431 | 1.4E | No. 1 | 1.552 | 12.75 |
| 432 | 1.4E | No. 1 | 1.196 | 12.50 |
| 433 | 1.4E | No. 1 | 1.379 | 12.69 |
| 434 | 1.4E | No. 1 | 1.281 | 12.75 |
| 435 | 1.4E | No. 1 | 1.209 | 12.44 |
| 436 | 1.4E | No. 1 | 1.489 | 12.13 |
| 437 | 1.4E | No. 1 | 1.553 | 12.75 |
| 438 | 1.4E | No. 1 | 1.458 | 12.81 |
| 439 | 1.4E | No. 1 | 1.433 | 12.69 |
| 440 | 1.4E | No. 1 | 1.515 | 12.58 |
| 441 | 1.4E | No. 2 | 1.491 | 13.10 |
| 442 | 1.4E | No. 1 | 1.295 | 13.81 |
| 443 | Cull | Cull | — | 13.21 |
| 444 | No. 1 | No. 1 | 1.127 | 13.17 |
| 445 | Cull | Cull | — | 12.83 |
| 446 | 1.4E | No. 1 | 1.335 | 12.73 |
| 447 | 1.4E | No. 1 | 1.225 | 12.85 |
| 448 | 1.4E | No. 1 | 1.180 | 11.94 |
| 449 | 1.4E | No. 1 | 1.175 | 12.81 |
| 450 | 1.4E | No. 1 | 1.226 | 12.83 |
| 452 | 1.4E | No. 3 | 1.406 | 12.33 |
| 453 | Cull | Cull | — | 12.75 |
| 454 | 1.9E | No. 1 | 1.826 | 12.79 |
| 455 | 1.4E | No. 1 | 1.666 | 13.38 |
| 457 | 1.4E | No. 2 | 1.461 | 12.54 |
| 458 | 1.4E | No. 1 | 1.328 | 12.44 |
| 459 | 1.4E | No. 2 | 1.703 | 12.67 |
| 460 | 1.4E | No. 1 | 1.719 | 12.73 |
| 461 | Cull | Cull | — | 12.69 |
| 462 | 1.4E | No. 1 | 1.707 | 12.73 |
| 463 | Cull | Cull | — | 13.21 |
| 464 | 1.4E | No. 1 | 1.592 | 12.71 |
| 465 | 1.4E | No. 1 | 1.427 | 12.75 |
| 466 | No. 1 | No. 1 | 1.123 | 12.88 |
| 467 | 1.4E | No. 3 | 1.304 | 12.46 |
| 469 | 1.4E | No. 1 | 1.363 | 14.85 |
| 470 | No. 1 | No. 1 | 1.133 | 14.54 |
| 471 | 1.4E | No. 1 | 1.478 | 14.60 |
| 472 | 1.4E | No. 1 | 1.292 | 14.31 |
| 473 | 1.4E | No. 1 | 1.219 | 14.60 |
| 474 | 1.4E | No. 1 | 1.470 | 14.71 |
| 475 | 1.4E | No. 2 | 1.588 | 14.75 |
| 476 | 1.4E | No. 1 | 1.249 | 14.67 |
| 477 | 1.4E | No. 1 | 1.243 | 14.60 |
| 478 | Cull | Cull | — | 14.79 |
| 479 | Cull | Cull | — | 15.40 |
| 480 | 1.4E | No. 1 | 1.371 | 14.81 |
| 481 | 1.4E | No. 3 | 1.209 | 15.88 |
| 482 | 1.4E | No. 1 | 1.537 | 14.29 |
| 483 | Cull | Cull | — | 14.52 |
| 484 | Cull | Cull | — | 15.10 |
| 485 | 1.4E | No. 1 | 1.284 | 14.73 |
| 486 | 1.4E | No. 1 | 1.254 | 15.00 |
| 487 | 1.4E | No. 1 | 1.245 | 15.10 |
| 488 | No.1 | No. 1 | 1.081 | 15.19 |
| 489 | 1.4E | No. 1 | 1.162 | 14.29 |
| 490 | 1.4E | No. 1 | 1.275 | 15.06 |
| 491 | 1.4E | No. 1 | 1.478 | 14.81 |
| 492 | 1.4E | No. 3 | 1.324 | 14.83 |
| 493 | 1.4E | No. 1 | 1.454 | 14.81 |
| 494 | Cull | Cull | — | 15.02 |
| 495 | 1.4E | No. 1 | 1.414 | 14.46 |
| 496 | 1.4E | No. 1 | 1.539 | 12.38 |
| 497 | 1.4E | No. 1 | 1.255 | 12.67 |
| 500 | 1.4E | No. 3 | 1.512 | 20.73 |
| 501 | 1.4E | No. 1 | 1.423 | 18.73 |
| 502 | 1.9E | No. 1 | 1.817 | 20.69 |
| 503 | 1.9E | No. 1 | 2.112 | 20.88 |
| 504 | 1.4E | No. 1 | 1.593 | 20.71 |
| 505 | 1.9E | No. 3 | 1.856 | 20.77 |
| 506 | 1.4E | No. 1 | 1.702 | 20.73 |
| 507 | 1.4E | No. 1 | 1.719 | 20.96 |
| 508 | 1.4E | No. 2 | 1.580 | 20.75 |
| 509 | 1.9E | No. 1 | 1.813 | 19.92 |
| 510 | 1.9E | No. 2 | 1.996 | 20.69 |
| 511 | 1.9E | No. 1 | 1.790 | 20.79 |
| 512 | Cull | Cull | — | 18.98 |
| 513 | 1.9E | No. 1 | 1.978 | 21.15 |
| 514 | 1.4E | No. 2 | 1.417 | 19.50 |
| 515 | 1.4E | No. 1 | 1.550 | 20.71 |
| 516 | 1.4E | No. 1 | 1.695 | 20.75 |
| 517 | 1.9E | No. 1 | 1.787 | 20.79 |
| 518 | 1.4E | No. 1 | 1.510 | 18.83 |
| 519 | 1.4E | No. 2 | 1.619 | 20.71 |
| 520 | Cull | Cull | — | 18.73 |
| 521 | 1.4E | No. 1 | 1.624 | 20.58 |
| 522 | 1.9E | No. 3 | 1.949 | 20.69 |
| 523 | 1.9E | No. 2 | 1.790 | 20.75 |
| 524 | 1.4E | No. 2 | 1.493 | 20.63 |

**Grade assignments for individual logs using option 1 (two mechanical grades, 1.9E and 1.4E) (continued)**

| Log number | MSR grade | Visual grade | MOE ($\times 10^6$ lb/in$^2$) | Length (ft) |
|---|---|---|---|---|
| 525 | 1.4E | No. 3 | 1.372 | 20.79 |
| 526 | 1.4E | No. 1 | 1.385 | 22.85 |
| 527 | Cull | Cull | — | 18.52 |
| 528 | 1.4E | No. 1 | 1.744 | 18.67 |
| 529 | 1.4E | No. 1 | 1.434 | 18.73 |
| 530 | 1.4E | No. 1 | 1.321 | 18.54 |
| 531 | 1.4E | No. 3 | 1.356 | 18.71 |
| 532 | 1.4E | No. 1 | 1.289 | 18.48 |
| 534 | 1.4E | No. 2 | 1.560 | 16.67 |
| 535 | Cull | Cull | — | 18.96 |
| 536 | Cull | Cull | — | 19.08 |
| 537 | 1.9E | No. 3 | 1.805 | 18.50 |
| 539 | 1.9E | No. 1 | 1.835 | 18.60 |
| 540 | 1.4E | No. 1 | 1.734 | 15.10 |
| 541 | 1.4E | No. 3 | 1.687 | 16.44 |
| 542 | 1.4E | No. 1 | 1.563 | 16.54 |
| 543 | 1.4E | No. 1 | 1.425 | 17.38 |
| 544 | 1.4E | No. 1 | 1.393 | 19.13 |
| 545 | 1.9E | No. 1 | 1.872 | 14.44 |
| 546 | 1.4E | No. 1 | 1.293 | 18.75 |
| 547 | 1.4E | No. 1 | 1.467 | 19.33 |
| 548 | Cull | Cull | — | 16.96 |
| 549 | 1.9E | No. 1 | 1.849 | 18.73 |
| 550 | 1.4E | No. 3 | 1.517 | 14.88 |
| 551 | Cull | Cull | — | 14.83 |
| 552 | 1.4E | No. 1 | 1.697 | 18.67 |
| 553 | 1.4E | No. 1 | 1.678 | 16.63 |
| 556 | 1.4E | No. 3 | 1.378 | 16.96 |
| 557 | Cull | Cull | — | 16.58 |
| 558 | 1.4E | No. 1 | 1.425 | 14.69 |
| 559 | No. 1 | No. 1 | 1.075 | 18.48 |
| 560 | 1.4E | No. 1 | 1.556 | 16.77 |
| 561 | 1.4E | No. 1 | 1.497 | 14.52 |
| 562 | Cull | Cull | — | 14.88 |
| 563 | Cull | Cull | — | 14.25 |
| 564 | Cull | Cull | — | 15.75 |
| 565 | 1.4E | No. 1 | 1.201 | 16.81 |
| 566 | Cull | Cull | — | 13.27 |
| 567 | Cull | Cull | — | 16.50 |
| 568 | 1.4E | No. 1 | 1.252 | 16.94 |
| 569 | 1.4E | No. 1 | 1.219 | 17.75 |
| 570 | 1.4E | No. 1 | 1.353 | 17.17 |
| 571 | 1.4E | No. 1 | 1.234 | 16.67 |
| 572 | 1.4E | No. 1 | 1.425 | 16.54 |
| 573 | 1.4E | No. 1 | 1.554 | 15.02 |
| 574 | Cull | Cull | — | 14.92 |
| 575 | Cull | Cull | — | 14.71 |
| 576 | 1.4E | No. 1 | 1.730 | 14.60 |
| 577 | 1.4E | No. 1 | 1.646 | 15.02 |
| 578 | 1.4E | No. 1 | 1.543 | 14.77 |
| 579 | Cull | Cull | — | 14.13 |
| 580 | 1.4E | No. 2 | 1.276 | 15.23 |
| 581 | 1.4E | No. 1 | 1.494 | 16.27 |
| 582 | 1.9E | No. 3 | 1.789 | 14.50 |
| 583 | 1.4E | No. 1 | 1.391 | 14.73 |
| 584 | Cull | Cull | .— | 16.71 |
| 585 | 1.4E | No. 1 | 1.684 | 14.44 |
| 586 | Cull | Cull | — | 14.63 |
| 587 | Cull | Cull | — | 14.83 |
| 588 | Cull | Cull | — | 14.44 |
| 589 | 1.4E | No. 1 | 1.471 | 14.69 |
| 590 | Cull | Cull | — | 14.58 |
| 591 | 1.4E | No. 1 | 1.613 | 14.81 |
| 592 | 1.4E | No. 1 | 1.208 | 14.46 |
| 597 | 1.4E | No. 1 | 1.240 | 15.02 |
| 598 | Cull | Cull | — | 14.63 |
| 599 | 1.4E | No. 1 | 1.535 | 14.42 |
| 600 | 1.4E | No. 1 | 1.430 | 14.75 |
| 601 | Cull | Cull | — | 14.75 |
| 602 | Cull | Cull | — | 14.54 |
| 603 | 1.4E | No. 1 | 1.283 | 14.73 |
| 605 | Cull | Cull | — | 15.04 |
| 606 | Cull | Cull | — | 14.73 |
| 607 | Cull | Cull | — | 14.75 |
| 608 | Cull | Cull | — | 14.25 |
| 609 | 1.4E | No. 1 | 1.286 | 14.52 |
| 610 | 1.4E | No. 1 | 1.642 | 14.88 |
| 611 | 1.4E | No. 1 | 1.659 | 20.52 |
| 612 | Cull | Cull | — | 19.00 |
| 613 | 1.4E | No. 1 | 1.689 | 18.75 |
| 614 | Cull | Cull | — | 19.15 |
| 615 | 1.4E | No. 1 | 1.394 | 18.98 |
| 616 | 1.4E | No. 1 | 1.453 | 18.75 |
| 617 | 1.4E | No. 1 | 1.678 | 18.83 |
| 618 | 1.4E | No. 1 | 1.299 | 18.60 |
| 619 | 1.4E | No. 3 | 1.511 | 20.71 |
| 620 | Cull | Cull | — | 18.42 |
| 621 | 1.4E | No. 1 | 1.286 | 18.54 |
| 622 | 1.4E | No. 1 | 1.419 | 20.73 |