# MECHANICAL PROPERTY ASSESSMENT FOR ESTABLISHING DESIGN VALUES OF WESTERN JUNIPER

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**Abstract.** Western juniper (*Juniperus occidentalis*) is a conifer that is native to Oregon, California, Washington, Nevada, and Idaho. Juniper is highly decay resistant and, therefore, is a popular choice for fence posts and landscape timbers. Forest management practices over the past 100 yr have resulted in an immense population increase in western juniper stands, transforming the grasslands/sagebrush biome into juniper forests. Landowners have been encouraged to cut back western juniper to restore grassland habitat, but there is no major market associated with juniper lumber. This study assessed the mechanical properties of western juniper to develop its design values for inclusion in the National Design Specification. Small clear samples were prepared from juniper harvested from three locations in eastern Oregon, one location in northeast California, and one location in southwest Idaho according to ASTM D143 for compression, bending, and shear. Average strength values were calculated and compared with similar wood species. Most

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properties were similar to those of other species, but modulus of elasticity was significantly lower. Compressive properties of western juniper also differed, with compression parallel-to-grain being lower and compression perpendicular-to-grain being relatively higher. Differences between species might be attributed to cell wall structure and distribution of lignin in the cells. Design values for western juniper were calculated using the strength values to establish allowable properties for visually graded lumber.

***Keywords:*** Bending properties, national design specifications, compression, green/dry ratio.

## INTRODUCTION

Western juniper is a coniferous tree species that grows from 6 to 18 m tall and to a diameter of approximately 300-900 mm. It thrives in a continental climate, with hot dry summers, cold winters, and precipitation between 230 and 355 mm/yr. Western juniper is native to California, Oregon, Idaho, and parts of Nevada and Washington. Juniper cover has drastically increased in the past century as a result of livestock grazing, increased amounts of $CO_2$, and more importantly fire suppression (Miller et al 2005). Western juniper has altered the natural habitat by shading out sagebrush and consuming excessive amounts of water (Bedell et al 1993). Vegetation decline has caused a corresponding reduction in wildlife species in juniper-forested areas (Bedell et al 1993). Landowners have been encouraged to thin juniper stands on their land to halt the spread of this species and restore the native grasses. The recommended method for western juniper removal is to fell and delimb the trees with chainsaws; in many cases, the logs and limbs are often left on-site to decay. This procedure can be costly, particularly in the absence of markets for the lumber, creating a significant cost burden for landowners.

Western juniper has been assessed for applications such as pencil stock, essential oils, and hardboard, but these markets have not developed to the extent required to encourage widespread restoration (Leavengood 2008). Western juniper has a highly decay-resistant heartwood because of the presence of extractives including cedrol (Highley 1995). Lignin levels are higher in western juniper heartwood than in most other naturally durable softwoods, such as western redcedar or redwood (Morrell et al 1999). In 2014, the State of Oregon approved western juniper heartwood as an alternative material for areas subjected to moisture and declared it "naturally durable." This allows western juniper to be used untreated for residential construction, most notably as a sill plate in a house. The natural durability of juniper also makes it a good fit for outdoor applications. The lack of existing markets for western juniper is due in part to the limited knowledge of the species as well as lack of design data, which are factored values for mechanical properties used by engineers and architects.

Design values listed in the National Design Specification (NDS) for timber construction creates several avenues for utilization of juniper both in structural as well as nonstructural applications. Government-funded building projects generally require a species to be listed in the NDS even for use in nonstructural applications such as landscaping or sign posts.

Burke (2008) reported average property values for western juniper but did not take the additional steps required to convert these results to design values. Unfortunately, Burke's raw (ie results for individual specimens) data were lost before they could be properly evaluated. This study characterized mechanical properties of western juniper and used these data to establish the design values.

The procedures for developing design values for a wood species in the NDS consist of testing samples from numerous geographic locations, ratifying the results with a certification agency, and then seeking approval from the American Lumber Standards Committee (ALSC). The first step in creating design values for a species is to establish a testing and material protocol that outlines the type of testing being conducted, number of tests being conducted, and the geographical origin of the material to be obtained. Once the material is procured from the listed geographical locations, the samples are prepared for testing according to relevant testing methods. The sample size needs to be sufficiently robust to obtain the lower 5th percentile. After testing, data are analyzed in collaboration with a licensed engineer in a certification agency, such as West Coast Lumber Inspection Bureau (WCLIB), and presented to ALSC for their approval and subsequent inclusion in the next edition of the NDS. Mechanical testing was performed on western juniper samples from different locations within the native range of the species. Adding western juniper to the design codes and standards will allow the use of juniper in commercial buildings. Increased utilization will stimulate the economy of rural areas where western juniper grows.

The objectives of this study were as follows:

1. To test multiple mechanical properties of western juniper as well as determine the green/dry ratio for shear and compression.
2. To analyze western juniper test data to formulate design values for the standards and codes.

## MATERIALS AND METHODS

### Materials

Lumber samples were randomly collected from Oregon, California, and Idaho. Five different western juniper processing facilities harvested and milled the juniper to size. The number of samples obtained from each state was based on the relative volume of timber present in that state. Oregon contained the most standing western juniper with approximately 66% of the total volume, followed by California with 21% and Idaho with 13% (FIA 2015). Sampling frequency was based on 240 samples per test, with replication from each state based on the volume of juniper in that state (Table 1). Because Oregon contained the highest volume of western juniper, the material was obtained from three different sites within Oregon, whereas samples were collected from only one site in each of the other states. The three locations for Oregon were based on the regions where western juniper predominated and represented three distinct geographical populations. The Oregon sites were in Lake County in South Central Oregon, Crook County in Central Oregon, and Harney County in Eastern Oregon. The California samples were obtained from Modoc County in northeast California; Idaho samples were obtained from Owyhee County in southwest Idaho. The method of material collection made it difficult to estimate the age of the original trees. Average stand ages for Lake County, Harney County, and Modoc County were approximately 120 yr, whereas Crook County contained trees ranging from 50 to 130 yr old. The stand age for Owyhee County in Idaho was unknown. The materials procured were either as 101.6 × 101.6 mm (4 × 4 in.) or 152.4 × 152.4 mm (6 × 6 in.) posts approximately 2.44 m long (8 ft.).

The posts were cut into specific sample dimensions for evaluating bending, compression parallel- and perpendicular-to-grain, and shear strength (Table 1). The number of samples for each test was derived by the WCLIB and stipulated in a testing plan submitted to the ALSC so that the data could be considered for inclusion in the NDS. A total of 240 samples were tested for each property. The samples were clear of any visible defects such as knots, decay, or wane (bark) and had straight grain. The posts were marked to define areas of clear wood before being bucked to length and then sawn to the specified sizes stipulated in ASTM Standard D143 (Table 1). The samples were cut as close as possible to a specific wood orientation for a given test. For example, in the bending standards, it states that the sample be loaded on the tangential surface (ASTM D143-14 2014). The samples were conditioned to constant weight at 20°C and 65% RH (an EMC of approximately 12%).

***Dry/green ratio samples.*** A green/dry property ratio was established to understand the difference in strength properties between green and dry samples. The samples used to develop the dry/green (DG) ratio were obtained from 30 unpeeled log sections 600-900-mm long that had

Table 1. Dimensions and replicates of samples used to evaluate material properties of western juniper.

| Region (standing timber volume) | Bending (25.4 × 25.4 × 406 mm) | Compression Para. (50.8 × 50.8 × 203 mm) | Compression Perp. (50.8 × 50.8 × 152 mm) | Shear (50.8 × 50.8 × 64 mm) |
|---|---|---|---|---|
| California (21%) | 50 (20.8%) | 50 (20.8%) | 50 (20.8%) | 50 (20.8%) |
| Idaho (13%) | 31 (12.9%) | 31 (12.9%) | 31 (12.9%) | 31 (12.9%) |
| Oregon (66%) | 159 (66.3%) | 159 (66.3%) | 159 (66.3%) | 159 (66.3%) |
| Total | 240 (100%) | 240 (100%) | 240 (100%) | 240 (100%) |

been end sealed to retain moisture. The logs were cut in 50.8 × 50.8-mm (2 × 2 in.) squares that were either 300 or 120 mm long. These pieces were then cut in half. One half was tested in shear or compression in the green condition, whereas the other half was conditioned to an MC of approximately 12% before testing. Thirty samples were performed per mechanical test on both green and dry specimens, creating a total of 120 samples.

## Methods

***Bending.*** Three-point bending tests were performed on 25.4 × 25.4 × 406.4-mm-long (1 × 1 × 16 in.) juniper beams as per ASTM D143. The samples were placed in the universal testing machine (UTM) on a span of 335.6 mm (14 in.) with the tangential surface nearest to the pith facing up. The samples were loaded at a rate of 2 mm/min. The deviation from the standard rate of 1.3 mm/min ensured that the testing took 6-12 min. The load/deflection curve was recorded and these data were used to calculate MOE and MOR using an Instron 5582 UTM with a 100-kN load cell and a round wooden load-bearing head connected to the crossarm using Eqs 1 and 2, respectively. Each failed sample was photographed to record the failure type as described in the ASTM Standard D143.

$$\mathrm{MOE} = \frac{PL^3}{48ID}, \tag{1}$$

where, $L$ is the Span (mm), $P$ is the concentrated center load (N) below the proportional limit, $D$ is the deflection at midspan using the crosshead deflection as reference (mm) resulting from $P$, and $I$ is the moment of inertia, a function of the beam's section (width × depth$^3$)/12.

$$\mathrm{MOR} = \frac{1.5PL}{bh^2}, \tag{2}$$

where, $h$ is depth of the beam, $b$ is the width of the beam, and $P$ is the breaking (maximum) load (N)

***Compression parallel.*** Compression parallel-to-grain tests were performed on 50.8 × 50.8 × 203.2-mm-long (2 × 2 × 8 in.) juniper samples on an Material Testing Systems (MTS) UTM with a 178-kN load cell using a pivoting base and flat rectangular load-bearing head. A pivoting base was used to ensure a uniform load distribution to each end of the sample. The crossarm applied a load at a rate of 1.3 mm/min until significant failure was observed visually. The compressive failure was then classified under six types of failure as described in ASTM Standard D143. Once the failure type was determined, the maximum load was recorded. The compressive strength of the sample was calculated using the maximum load and the cross-sectional area.

***Compression perpendicular.*** Compression perpendicular-to-grain tests were performed on 50.8 × 50.8 × 152.4-mm-long (2 × 2 × 6 in.) juniper samples on an Instron 5582 UTM using a 100 kN load cell. A rectangular 50.8-mm-wide load-bearing plate was attached to the crossarm. The surface of the load-bearing plate during testing applied a load on the radial surface of the sample, which was situated on a leveled steel plate. The load-bearing plate compressed a 50.8 × 50.8-mm (2 × 2 in.) middle section of the sample. The crossarm was then lowered at a rate of 0.305 mm/min. The test was stopped after an extension of 2.5 mm was reached. Once the test was complete, the area where the sample was compressed was marked and the maximum load was recorded.

A load was applied laterally to the tracheids during the compression⊥ test. This load collapsed the cell walls, and once this happened, the compressive stress started to plateau. Once the tracheids were fully crushed, the load began to increase again. This made it difficult to obtain a maximum force (Ali et al 2014). As a result, failure in compression⊥ does not cause a break within the wood but rather deformation of the loaded area. The common failure was a crushed area under the load head that varied in depth. For this reason, compressive strength was calculated using the force at 1-mm deflection as described in ASTM Standard D143. The load/deflection curve was used to obtain the compressive strength using the load at 1 mm of deflection with the formula:

$$\text{Compressive Strength} = \frac{P_{1\text{mm}}}{L_{\text{sample}} \times w_{\text{load head}}}, \tag{3}$$

where, $P_{1\text{mm}}$ is the load at 1 mm, $L_{\text{sample}}$ is the length of the sample (mm), and $w_{\text{load head}}$ is the width of load head (mm).

***Shear.*** Shear tests were performed on 50.8 × 50.8 × 63.5-mm long (2 × 2 × 2.5 in.) samples with a 12.7 × 19.05 mm (0.5 × 0.75 in.) notch removed to produce shear failure in the sample. The shear area was calculated by measuring the length and width of the remaining area under the notch. The test was performed on an Instron 5582 UTM using a 100-kN load cell. The setup used a shear tool that applied a force to the area under the notch loaded at a rate of 0.6 mm/min (0.024 in./min) until failure as described in the ASTM D143 standard. Maximum force was recorded.

***MC and density.*** MC and specific gravity (SG) were calculated following ASTM standards: ASTM D4442-16 (2016) Method B and ASTM D2395-14e1 (2014) Method A, respectively. A 25.4 × 25.4 × 50.8-mm-long (1 × 1 × 2 in.) section was cut from each sample subjected to mechanical testing. From bending samples, a 25.4 × 25.4 × 25.4-mm (1 × 1 × 1 in.) sample was cut from the end of the beam for determination of MC and SG.

***DG ratio.*** The green average strength property ($x_{\text{green}}$) and the dry average strength property ($x_{\text{dry}}$) for shear and compression perpendicular-to-grain tests were divided to obtain the initial DG ratio.

$$\text{Initial DG} = \frac{x_{\text{dry}}}{x_{\text{green}}}. \tag{4}$$

The average equilibrated sample MC was used to adjust the DG ratio. The initial DG ratio was then adjusted to 12% MC using the FSP of 27% and the average MC of both tests to create an adjustment factor. This adjustment was used on dried or equilibrated samples.

$$12\% \text{ MC adjustment factor} = \left[\frac{\text{FSP} - \text{MC}}{\text{FSP} - 12}\right]. \tag{5}$$

The adjustment factor was applied to the initial DG ratio to create the adjusted DG ratio (DG Ratio′).

$$\text{DG Ratio}' = \frac{\text{Initial DG Ratio}}{(12\% \text{ MC adjustment factor})}. \tag{6}$$

These ratios were then used to create design values for shear and compression perpendicular-to-grain.

***Design value calculations.*** Design values were calculated using the data for each mechanical property using equations from the ASTM Standards D245 and D1990. The procedures for MOR and compression parallel-to-grain were the same, whereas the other three properties used different procedures. Several factors were applied to the strength properties, including MC adjustments and volume adjustments. Described in the following paragraphs are the factors that were used in calculating the design values.

The seasoning factor adjusted the MC for each sample strength property to 15% MC:

$$S2 = S1 + \left[\frac{S1 - B1}{B2 - M1}\right](M1 - M2), \quad (7)$$

where, $M1$ is the MC at testing (%), $M2$ is the MC of 15%,

$S1$ is the strength property at $M1$ (MPa), $S2$ is the strength property at 15% MC (MPa), and $B1$ and $B2$ are constants: MOR ($B1 = 2415$, $B2 = 40$) and ultimate compressive stress (UCS) ($B1 = 1400$ and $B2 = 34$).

The 5% exclusion limit was then calculated by subtracting 1.645* the standard deviation from the mean value, ie the lower 5% value for a standard normal distribution.

A size factor was used to account for the testing dimensions compared with lumber dimensions using the formula:

$$F = \left(\frac{ds}{d}\right)^{1/9}, \quad (8)$$

where, $F$ is a size factor, $ds$ is the sample depth, and $d$ is the net surface depth.

A volume adjustment factor was used on the values depending on the different grade dimensions to account for different dimensions within a lumber grade using the formula:

$$F2 = F1\left(\frac{W1}{W2}\right)^{w}\left(\frac{L1}{L2}\right)^{l}, \quad (9)$$

where, $F1$ is the property value at volume 1, $F2$ is the property value at volume 2, $W1$ is the width at $F1$, $W2$ is the width at $F2$, $L1$ is the length at $F1$, $L2$ is the length at $F2$, $w$ is a constant for width (MOR $= 0.29$, UCS $= 0.13$, MOE $= 0$), and $l$ is a constant for length (MOR $= 0.14$, UCS & MOE $= 0$)

Strength ratio factors were obtained from ASTM Standard D245, sections 4.1.6 and 4.2.3 note 2, for compression perpendicular-to-grain and shear. The strength ratio factors for the other properties were calculated by the WCLIB and are presented in Table 2.

The reduction factors were obtained from ASTM Standard D245, section 6.2-Table 8, whereas the seasoning factors for compression perpendicular-to-grain and shear were obtained from ASTM Standard D245, section 7.1-Table 10 (ASTM Standard D245-06 2011). The step-by-step process for calculating design values for each property can be seen in Table 3.

***Statistical analysis of mechanical tests.*** The data were analyzed in RStudio (R ver. 3.2.2) using a one-way analysis of variance (ANOVA) test and a Tukey–Kramer test to examine differences between sampling sources (sites) in the mechanical tests. The assumptions of these tests were verified using a Shapiro–Wilk test to evaluate normality and a Fligner–Killeen test to evaluate equal variance at $\alpha = 0.05$. These statistical tests were performed on MOR, compression parallel-to-grain, and shear tests. Because of violating the assumption for equal variance, the MOE and compression perpendicular-to-grain tests were analyzed using a Kruskal–Wallis test.

The one-way ANOVA test compared the sample means between the locations to determine if sample means differed significantly from each other. Locations were further analyzed using a Tukey–Kramer test multiple comparison procedure.

The Kruskal–Wallis test is a nonparametric test method, which is a common alternative to a one-way ANOVA when assumptions are violated. This method ranks the strength values from highest to lowest in all the locations and uses the ranks in a one-way ANOVA to determine if there were any significant differences between the locations. The kruskalmc method in R, which is a modified Kruskal–Wallis test, was used to

Table 2. Factors from the ASTM standard D245 and the WCLIB.

| Grade | Comp para[a] | MOR[a] | MOE[a] | Comp perp | Shear para |
|---|---|---|---|---|---|
| Strength ratio factors | | | | | |
| SS | 0.69 | 0.65 | 1.00 | 1.00 | 0.50 |
| No. 1 | 0.62 | 0.55 | 1.00 | 1.00 | 0.50 |
| No. 2 | 0.52 | 0.45 | 0.90 | 1.00 | 0.50 |
| No. 3 | 0.30 | 0.26 | 0.81 | 1.00 | 0.50 |
| Stud | 0.30 | 0.26 | 0.81 | 1.00 | 0.50 |
| Construction | 0.56 | 0.34 | 0.85 | 1.00 | 0.50 |
| Standard | 0.46 | 0.19 | 0.77 | 1.00 | 0.50 |
| Utility | 0.30 | 0.09 | 0.72 | 1.00 | 0.50 |
| Other factors | | | | | |
| Reduction factor | 1.90 | 2.10 | 0.94 | 1.67 | 2.10 |
| Seasoning factor | Eq 11 | Eq 11 | Eq 11 | 1.08 | 1.50 |

[a] Strength ratios calculated by the WCLIB.
WCIB, West Coast Lumber Inspection Bureau.

identify differences between groups (Siegel and Castellan 1988).

## RESULTS AND DISCUSSION

Results of all tests are summarized in Table 4 along with a statistical analysis for between-site comparison. Table 5 compares average strength properties for western juniper with other wood species including data from Burke (2008).

### Three-Point Bending Test

***MOE.*** Mean MOE for samples from all locations was 3948.5 MPa (Coefficient of Variation (COV) = 27%) (Table 4). Samples with the highest MOE were obtained from Klamath County with an MOE of 4629.3 MPa (COV = 16%), whereas the lowest MOE was found in samples from Idaho (2739.3 MPa) (COV = 17%) (Table 4). There was evidence that mean MOE of the western juniper varied significantly with location (ANOVA, $p$-value <0.0001). MOE of samples from Klamath County and California were significantly greater than those from the other locations (Tukey, $p$-values <0.05). MOE of samples from Prineville and Burns differed significantly from all other locations (Tukey, $p$-values <0.05). MOE of samples from Idaho were significantly lower than those from all other locations (Tukey, $p$-values <0.05).

Mean MOE of western juniper was lower than those for all of the comparator wood species (Table 5). MOE of other wood species similar to western juniper, ie a naturally durable conifer with a similar SG, ranged between 7000 and 8900 MPa. Low MOE of the western juniper samples may be due to differences in tracheid length and diameter, but further characterization of the anatomical differences between samples is required. Western juniper tracheids average 1.6 mm in length, whereas tracheids in most other softwoods range from 3 to 4 mm (Myers et al 1998). Shorter

Table 3. Step-by-step process used to calculate design values of different wood properties.

| | Steps to calculate design values | | | | |
|---|---|---|---|---|---|
| Steps | Comp para | MOR | Comp perp | Shear para | MOE |
| 1 | Seasoning factor | Seasoning factor | Total average | 5%EL average | Total average |
| 2 | 5%EL average | 5%EL average | DG ratio | DG ratio | Strength ratio |
| 3 | Size factor | Size factor | 12% DG adjustment | 12% DG adjustment | Reduction factor |
| 4 | Strength ratio | Strength ratio | Strength ratio | Strength ratio | x |
| 5 | Reduction factor | reduction factor | Seasoning factor | Seasoning factor | x |
| 6 | Volume adjustment factor | Volume adjustment factor | reduction factor | reduction factor | x |

DG, dry/green.

Table 4. Mean strength properties of western juniper samples from five locations in the growing region.

| | Mean Strength Properties (MPa) | | | | | |
|---|---|---|---|---|---|---|
| Means | Burns | Klamath | Prineville | California | Idaho | Average |
| Comp∥ | 27.30 | 32.58 | 28.63 | 30.41 | 26.86 | 29.35 |
| COV (%) | 11 | 10 | 10 | 11 | 12 | 13 |
| Tukey | C | A | C | B | C | |
| Comp⊥ | 6.88 | 7.22 | 7.71 | 6.67 | 5.71 | 6.95 |
| COV (%) | 20 | 18 | 22 | 21 | 22 | 22 |
| Kruskalmc | B | AB | A | B | C | |
| Shear | 5.96 | 7.27 | 8.00 | 7.70 | 8.24 | 7.35 |
| COV (%) | 17 | 17 | 14 | 15 | 19 | 47 |
| Tukey | C | B | A | AB | A | |
| MOE | 3561.37 | 4629.80 | 3744.20 | 4603.64 | 2739.28 | 3948.48 |
| COV (%) | 29 | 16 | 18 | 25 | 17 | 27 |
| Kruskalmc | A | B | A | B | C | |
| MOR | 57.17 | 60.59 | 61.57 | 57.03 | 53.92 | 58.44 |
| COV (%) | 13 | 15 | 12 | 15 | 13 | 14 |
| Tukey | BC | AB | A | BC | C | |

tracheids in western juniper could behave similarly to juvenile wood, which has tracheids that are only 25-30% as long as those in mature wood and is associated with 15-50% reduction in mechanical properties (Shmulsky and Jones 2011). Western juniper tracheid diameters range from 0.012 to 0.031 mm, which is also smaller than those for most softwoods (Myers et al 1998). Tracheid length and diameter tend to be positively correlated with increased MOE ($r^2 = 0.684$ and $r^2 = 0.678$, respectively) (Kiaei et al 2013). The decreased mean MOE of the samples from Idaho (2739.28 MPa) may be due to the effects of lower precipitation in this area (Table 6) on tracheid length, diameter, and proportion of late wood, but more study would be required to confirm this premise.

***MOR.*** Average MOR across all locations was 58.44 MPa with a COV of 14% (Table 4). Samples with the highest MOR originated in Prineville (61.57 MPa) (COV = 12%), whereas the lowest MOR was found in samples from Idaho (53.92 MPa) (Table 4). There was evidence that mean MOR of the western juniper varied significantly with location (ANOVA, *p*-value <0.0001). MOR of samples from Prineville and Klamath did not differ significantly (Tukey, *p*-value = 0.95), nor did those from Klamath, Burns, or California (Tukey, *p*-values >0.05). The MOR of samples from Idaho did not differ from those from Burns or California (Tukey, *p*-values >0.05) but differed significantly from those from Prineville and Klamath (Tukey, *p*-value <0.05). Failure modes of the test samples

Table 5. Comparison between mean strength properties and specific gravity (SG) of western juniper and similar wood species.

| | Mean strength properties (MPa) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Western juniper | | | | | | | | |
| | Present study | Burke study | Western redcedar | Eastern redcedar | Incense-cedar | P.O. cedar | Eastern Hemlock | Ponderosa pine | Douglas-fir |
| Comp∥ | 29.35 | 35.65 | 31.40 | 41.50 | 35.90 | 43.10 | 37.30 | 36.70 | 51.20 |
| Comp⊥ | 6.95 | X | 3.20 | 6.30 | 4.10 | 5.00 | 4.50 | 4.00 | 5.20 |
| Shear | 7.35 | 8.83 | 6.80 | X | 6.10 | 9.40 | 7.30 | 7.80 | 8.90 |
| MOE | 3948 | 4915 | 7700 | 6100 | 7200 | 11,700 | 8300 | 8900 | 12,600 |
| MOR | 58.44 | 64.49 | 51.71 | 61.00 | 55.16 | 88.00 | 61.00 | 65.00 | 87.00 |
| SG @ 12% | 0.40 | 0.39 | 0.32 | 0.47 | 0.37 | 0.43 | 0.40 | 0.40 | 0.50 |

Source: Burke (2008), USDA (2010).

Table 6. Average rainfall, snowfall, and elevation for counties where western juniper was collected.

| | Annual average climate data | | | | |
|---|---|---|---|---|---|
| | Burns (Harney) | Prineville (Crook) | Klamath (Lake) | California (Modoc) | Idaho (Owyhee) |
| Rainfall (cm) | 27.74 | 30.99 | 25.91 | 39.55 | 19.30 |
| Snowfall (cm) | 44.55 | 104.01 | 111.28 | 120.29 | 9.91 |
| Elevation (m) | 1478.58 | 1328.01 | 1563.62 | 1516.08 | 1457.25 |

Source of Data: National Climatic Data Center (NOAA).

were typical for bending tests with failure in tension that leads to shear as described in ASTM Standard D143 (ASTM D198-15 2015).

Mean MOR of western juniper was similar to that of other species such as western redcedar and incense-cedar (Table 5). MOR tends to be correlated with SG and western juniper followed this pattern (USDA 2010). Mean MOR of western juniper did not deviate from the other species as much as the MOE and this may, again, be explained by cell dimensions. MOR is strongly correlated with tracheid diameter ($r^2 = 0.47$) but is poorly correlated with tracheid length ($r^2 = 0.08$) (Kiaei et al 2013). MOE is influenced by both the length and diameter of the tracheids.

## Compression Parallel-to-Grain (||) Test

Compressive strength|| for samples from all locations averaged 29.35 MPa with a COV of 13% (Table 4). The highest compressive strength was observed in samples from Klamath (32.85 MPa and COV = 10%), whereas the lowest compressive strength was observed in samples from Idaho (26.86 MPa and COV = 12%) (Table 4). There was evidence that mean compressive strength of western juniper varied significantly with location (ANOVA, $p$-value $<0.0001$). Compressive strength in samples from the Klamath and California locations were significantly greater than those from the other locations ($p$-values $<0.05$).

Compression|| failures in western juniper were similar to those found in other wood species, with cell wall buckling under the applied stress. Many samples developed a crushing band where buckling occurred. Most of the samples failed in shear as defined in ASTM Standard ASTM D143-14 (2014). In shearing, the crushing band had an angle of 45 degrees or greater with the top of the sample (Crushing and wedge split failure types were also observed.

Mean compressive strength of western juniper was lower than that of other similar wood species such as western redcedar (*Thuja plicata*) and eastern redcedar (*Juniperus virginiana*) (Table 4) (USDA 2010). Compression|| tends to be correlated with SG (USDA 2010), but western juniper had lower compressive strength than species with lower SG. Decreased compressive strength could be due to the tracheid diameters of western juniper, which were smaller than that of most softwoods, but equivalent to the diameter of most hardwoods (Myers et al 1998). Hardwoods have been shown to have lower compressive strength in the parallel-to-grain direction than in softwoods (USDA 2010). Western juniper wood also has a fairly uniform tracheid cell wall thickness. The growth rings have only a very narrow band of denser latewood and this may have also affected load capacity (USDA 2010).

Differences in compression strength|| could also result from the climate where the trees were grown, competition in the stand, and as precipitation. The relationships between average rainfall, snowfall, elevation, and compressive strength were examined by county where the samples were collected. These data must be viewed with caution because microclimate can vary widely, even in relative close proximity (Table 6). All the samples grew in areas with similar elevations, but precipitation varied widely.

Moisture influences both quantity and quality of wood produced. Lower precipitation has obvious effects on growth rate (ie the number of tracheids produced) and lumen diameter. The pattern of precipitation may also affect wood quality (Drew et al 2012). For example, snowfall may be more conducive to steady growth because it would allow more controlled water release into the soil.

The Idaho site received the lowest average precipitation in terms of rain and snow, and materials from this area also had significantly lower compression parallel-to-grain strength than those from the Oregon sites, which all received more precipitation as either snow or rain. The inconsistent relationship between precipitation and strength illustrates the difficulty in using weather data collected from a single site to characterize a broader geographic area. Precipitation can vary widely in relatively small areas and can vary widely over time. This makes it difficult to use average data for comparative purposes.

## Compression Perpendicular-to-Grain (⊥) Test

Mean compressive strength⊥ for all locations was approximately 6.95 MPa with a COV of 22% (Table 4). The highest compressive strength was observed in samples from Prineville (7.71 MPa; COV = 22%), whereas the lowest compressive strength was observed in the samples from Idaho (5.71 MPa, COV = 22%) (Table 4). There was statistical evidence that the mean compressive strength of western juniper differed significantly between locations (Kruskal–Wallis, *p*-value <0.0001). There was no significant difference in compressive strength⊥ in samples from Prineville, Burns, Klamath, or California locations. The compressive strength of samples from Idaho did not differ significantly from those from California but did differ significantly from the Oregon locations. Materials from Prineville also had the highest SG (0.43). The lowest mean SG (0.38) was found in samples from Burns, but these samples had the second highest mean compressive strength (6.88 MPa). COV% tends to be high for this wood property and therefore high variability can be expected. Samples from the Idaho location were also highly variable with a COV for SG of 14%, whereas COVs for samples from the other locations were between 7% and 8%.

Compressive strength of western juniper was greater than that reported for incense-cedar and eastern redcedar, which have compressive strengths of 4.10 and 6.30 MPa, respectively (Table 5). Compressive strength is generally correlated with SG (USDA 2010). However, compressive strength of western juniper was higher than that of Port-Orford-cedar, which has a compressive strength of 5 MPa in the perpendicular direction and an SG of 0.43. The COV for compressive strength⊥ was 20%. Typically, compression⊥ has the highest variability among all the measurable properties. Typical variability for compressive strength⊥ is 28% (USDA 2010).

Compression⊥ of western juniper was higher than that reported for many softwood species used in structural applications, such as Douglas-fir and ponderosa pine (Table 5). High compressive strength could be due to the smaller tracheid diameter in western juniper. These uncharacteristically smaller tracheid diameters are similar to the fibers found in diffuse-porous hardwoods (Myers et al 1998). Consequently, the compressive strength⊥ might be similar to that found in hardwood species given that hardwoods typically have higher compressive strength than softwoods in the perpendicular direction (USDA 2010). The second factor that could have contributed to the increase in strength is the lignin content. Western juniper contains an average of 35.5%, which is the highest lignin content of any domestic softwood or hardwood (Myers et al 1998). Lignin is considered the bonding agent between cellulose and hemicellulose within the cell wall. Lignin may also enhance polymer interactions that increase cell rigidity (Shmulsky and David 2011). These two factors may have produced a higher yield strength, thereby increasing tracheid resistance to collapse. These factors could also explain the high compressive strength found in eastern redcedar, which also has smaller diameter tracheids (2.15 mm).

## Shear Block Test

Mean shear strength for samples from all locations was approximately 7.35 MPa (COV = 19%) (Table 4). Samples with the highest shear strength originated in Idaho with a strength of 8.24 MPa (COV = 19%), whereas the lowest shear strength of 5.96 MPa (COV = 17%) was observed in samples from Burns, OR (Table 4). There was evidence that the mean shear strength of western juniper varied because of location (ANOVA, *p*-value <0.0001). Samples from Idaho, Prineville, and California did not differ significantly in shear strength (Tukey, *p*-values >0.05). Shear strength in samples from the Klamath County and California locations did not differ significantly (Tukey, *p*-values = 0.35), but there was evidence that samples from Klamath County differed significantly from those from Idaho and Prineville (Tukey, *p*-values <0.05). Shear strength in samples from Burns were the lowest and differed significantly from all other sites (Tukey, *p*-values <0.05).

Shear strength of western juniper was greater than that reported for western redcedar (6.80 MPa) and incense-cedar (6.10 MPa) (Table 5). Eastern redcedar had the highest SG, whereas SGs for the other species were similar or lower. Shear strength tends to be correlated with SG, which can be seen when comparing juniper to the other similar species (USDA 2010).

Mean shear strength was highest in samples from Idaho, averaging 8.24 MPa (Table 4). This was interesting because other properties in samples from the Idaho location tended to be lower. Shear strength of Idaho samples was similar to that for some Douglas-fir samples (coastal = 7.8 MPa and interior west = 8.9 MPa) (USDA 2010). Higher shear strength in Idaho samples could be a result of tracheids with a smaller diameter due to lower precipitation in the area (Drew et al 2012). The smaller tracheids in the Idaho samples could be acting similarly to the fibers in diffuse-porous hardwoods, which typically have higher shear strength than softwoods (USDA 2010). Another factor that could affect properties was the position in the stem where the samples originated. For example, samples near the pith would tend to contain higher percentages of juvenile wood (Shmulsky and David 2011); however, the Idaho samples mainly contained sapwood, suggesting that they were taken further out from the pith. Samples from the other locations contained either all heartwood or had some amount of heartwood within them. The presence of juvenile wood could also have influenced the results because these materials can be as much as 40% weather than mature wood (Shmulsky and David 2011). However, it would be difficult to determine the presence of juvenile wood in our samples because they were obtained as aquare posts.

## Green/Dry Ratio of Compression Perpendicular-to-Grain and Shear

The compression⊥ values for DG samples differed significantly from the original samples tested. The original compression⊥ tests contained 240 samples spread across three states and five sampling sites, whereas the DG ratio samples were obtained from a single sample site (Prineville, OR). Differences noted between the main and the DG samples from Prineville location could reflect geographic location or tree age. The samplesfor the main data were harvested from a stand with trees approximately 50-130 yr old, whereas the DG samples were obtained from a different stand with an unknown age.

Green compressive strength of western juniper averaged 5.56 MPa, whereas mean dry compressive strength was 6.48 MPa. The initial DG ratio for the compressive strength was 1.17, and adjusting this ratio for 12% MC produced a value of 1.56.

The green shear strength of western juniper had a mean of 6.21 MPa, whereas mean dry shear strength was 7.70 MPa. The initial DG ratio for the shear strength was 1.24 and adjusting this ratio for 12% MC produced a value 1.68.

Shear strength for dry western juniper was similar to the values reported from the 240 small clear samples (7.35 MPa), whereas the compression strength was lower than the first samples tested.

Green shear strength was lower than for dry samples, for both tests. This was expected because of the effect of increasing MC above the FSP on wood properties (USDA 2010; Shmulsky and David 2011). Green samples were validated as green in that the MC for all specimens exceeded the FSP of 27% for this species.

## Strength Values

Calculated strength values in the present study differed from those found by Burke (2008). MOE and MOR were 20% and 9% lower, respectively, than values reported by Burke (2008). Differences could have resulted from sample site selection, tree selection, or load rate. Samples from the work of Burke (2008) were collected from similar areas in this study, excluding the Idaho site. Excluding the shear values, samples from Idaho had the lowest average values for all other properties. These lower values reduced the overall averages. The trees in the Burke study were specifically selected for stem form, height, diameter, and crown morphology, with no defects, whereas this study used materials that were randomly selected from commercial products (Burke 2008).

## Design Values

The mechanical test results were used to calculate base design values for all sample locations and presented in Table 7. An example of the process for creating design values is illustrated in the following paragraphs, for MOR and MOE.

The MOR values were first adjusted to 15% MC by applying an MC factor (Eq 7). The MC adjusted values were averaged and the 5% exclusion limit was calculated and subsequently adjusted from a 25.4-mm thickness to an 88.9-mm thickness (Eq 8), the typical structural lumber dimension. A strength ratio factor was applied to determine values for each of the eight grades (Table 2). A reduction factor was applied to account for the load duration and safety factors (Table 2). The last step in developing the design values for MOR was to adjust the volume of each grade (Eq 9) as strength may vary by dimensions.

Average values were used for MOE design values, because design is based on strength rather than stiffness. A strength ratio factor was applied to the average based on the lumber grade (Table 2), then a reduction factor was applied to account for load duration and safety (Table 3). These factors are property dependent.

The values presented in Table 7 are design values calculated by the authors and are in the process of approval from ALSC. The readers are advised to use NDS-listed design values for the purpose of engineering design.

Table 7. Base design values for various grades of western juniper lumber using data obtained from different areas of the growing region.

| | Base design values (MPa) | | | | |
|---|---|---|---|---|---|
| Grade | Comp∥ | MOE | MOR | Comp⊥ | Shear |
| SS | 6.59 | 3582.50 | 6.46 | 5.35 | 0.86 |
| No. 1 | 5.92 | 3582.50 | 5.46 | 5.35 | 0.86 |
| No. 2 | 4.96 | 3224.25 | 4.47 | 5.35 | 0.86 |
| No. 3 | 2.86 | 2883.91 | 2.58 | 5.35 | 0.86 |
| Stud | 3.14 | 2883.91 | 3.50 | 5.35 | 0.86 |
| Construction | 6.22 | 3027.21 | 5.09 | 5.35 | 0.86 |
| Standard | 5.11 | 2758.52 | 2.84 | 5.35 | 0.86 |
| Utility | 3.33 | 2579.40 | 1.35 | 5.35 | 0.86 |

## CONCLUSIONS

Mechanical properties, such as flexural strength, stiffness, compression (parallel and perpendicular), and shear for western juniper, were evaluated using 240 small clear specimens. Western juniper lumber had material properties that were similar to those for comparable species of similar SG, although the small tracheid diameter may have affected compressive properties. Properties varied with site, but there appeared to be no consistent relationship between climate, notably rainfall and properties. Calculated design values should allow western juniper to be used in structural applications, creating financial incentives for harvesting this species to help restore rangelands.

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