EFFECT OF MOISTURE CONTENT ON DOWEL-BEARING STRENGTH

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ABSTRACT

Dowel bearing strength (embedment strength) is a critical component of wood connection design. Previous tests have concentrated on defining the relationship between dowel-bearing strength, specific gravity, and fastener characteristics such as diameter. However, because adoption of yield theory in defining connection strength is relatively new in the United States, few studies have been conducted that completely define the factors influencing dowel-bearing strength. One such factor is moisture content. In this study, the dowel-bearing strength of two groups of specimens was determined. One group was made up of approximately 200 clear Southern Pine pieces distributed evenly among five different moisture content environments (4%, 6%, 12%, 19%, and green) and loaded with 12.7-mm- (0.5-in.-) diameter bolts. The second group included Southern Pine, Douglas Fir–Larch, and Spruce–Pine–Fir specimens in two moisture content environments (6% and 20+%) that were loaded with 3.33-mm (0.131-in.) (8d) smooth shank nails. An empirical linear relationship was developed between dowel-bearing strength and moisture content using the first group of specimens, which compared favorably with results from the second group. These results show that the dowel-bearing strength–moisture content relationship was not dependent on species or fastener type, and therefore, those parameters were not included in the model. Auxiliary tests verified previous research that has shown that dowel-bearing strength (parallel-to-grain) is positively correlated with ultimate parallel-to-grain compression strength.

Keywords: Wood, moisture content, dowel-bearing strength, embedment strength, compression stress, mechanical fasteners.

INTRODUCTION

Editions of the National Design Specification for Wood Construction (NDS) prior to 1991 based allowable lateral strength values for dowel fasteners (nails, screws, and bolts) on empirical equations. The 1991 NDS (AF&PA 1991) first adopted a yield model design methodology for laterally loaded, single-fastener connections. Since then, the 1996 Load and Resistance Factor Design for Engineered Wood Construction (LRFD) adopted the yield model for its laterally loaded connection provisions (ASCE 1996). This yield model has been referred to as the European yield model (EYM) because it was first developed in Europe by Johansen (1949).

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The yield model is based on the interaction of the bending resistance of the fastener and the crushing or embedment strength of the wood around the fastener during loading. This embedment strength, referred to as dowel-bearing strength in the United States, has been shown to be related to wood density for both bolts and nails (Smith et al. 1988; Wilkinson 1991). However, because the application of the EYM to design is relatively new in the United States, few studies have been conducted that completely define the factors influencing dowel-bearing strength; one such factor is moisture content (MC).

The objective of this research was to define the effect of MC on the dowel-bearing strength of several wood species groupings typical of those used in light-frame wood construction in the United States, namely Southern Pine, Douglas Fir–Larch, and Spruce–Pine–Fir. The intention was to develop a model based on tests of matched samples of clear Southern Pine specimens at five MC levels, isolating the effect of MC. Results of previous tests on Douglas–Fir, Spruce–Pine–Fir, and a second Southern Pine group at just two MC levels were then analyzed to extend the model to different species groups.

BACKGROUND

The Wood Handbook (Forest Products Laboratory 1999) provides a general discussion of the effect of MC on clear wood strength properties. It has been widely accepted that as MC goes from green to dry, the strength properties of wood increase. However, as Green and Kretschmann (1994) discuss and verify, there is growing evidence that different strength and stiffness properties are affected to varying degrees by changing levels of MC. For example, the bending modulus of elasticity (MOE) of clear Southern Pine increases linearly with drying from green to 4% MC, whereas MOE of compression parallel-to-grain increases linearly with drying from green to about 6% MC, then increases at a slower rate or remains constant with further drying. Other properties, such as ultimate tension stress parallel- and perpendicular-to-grain, peak in the range of 7% to 13% MC, then decrease with further drying.

The nominal single-bolt connection value is dependent on the joint geometry (thickness of main and side members), bolt diameter, dowel bending-yield strength, dowel-bearing strength, and direction of load to the grain. Yield expressions relating these parameters were developed by Johansen (1949) using a static analysis that assumes the wood and the bolt are both perfectly plastic. After nearly a decade of development, the yield model became the standard for dowel connection design in the 1991 NDS and is applicable to all types of dowel fasteners—nails, lag screws, and bolts (Aune and Patton–Mallory 1986; McLain 1992; McLain and Thangjitham 1983; Soltis and Wilkinson 1987; Soltis et al. 1986; Wilkinson 1993). The yield model theory selects the worst case of yield modes based on different possibilities of wood bearing and nail bending. Mode I is a wood-bearing failure in either the main or side member; mode II is a rotation of the fastener in the joint without bending; modes III and IV are a combination of wood-bearing failure and one or more plastic hinge yield formations in the fastener.

For a three-member bolted joint, the lateral design load Z (N) of a single bolt is determined by the minimum of the following yield expressions:

$$Z = \frac{Dt_m F_{em}}{4K_\theta} \qquad \text{Mode I}_m \qquad (1)$$

$$Z = \frac{Dt_s F_{es}}{4K_\theta} \qquad \text{Mode I}_s \qquad (2)$$

$$Z = \frac{k_3 D t_s F_{em}}{3.2(2 + R_e)K_\theta} \qquad \text{Mode III}_s \qquad (3)$$

$$Z = \frac{D^2}{3.2K_\theta}\sqrt{\frac{2F_{em}F_{yb}}{3(1 + R_e)}} \qquad \text{Mode IV} \qquad (4)$$

where

$$k_3 = -1 + \sqrt{\frac{2(1 + R_e)}{R_e} + \frac{2F_{yb}(2 + R_e)D^2}{3F_{em}t_s^2}}$$

$R_e = F_{em}/F_{es}$; F_{em} = dowel-bending strength of the main member (MPa), F_{es} = dowel-bending strength of the side member (MPa), t_m = main member thickness (mm), t_s = side member thickness (mm), F_{yb} = nail-bending yield stress (Pa), D = nominal bolt diameter (mm), $K_\theta = 1 + (\theta_{max}/360°)$, and θ_{max} = maximum angle of load to grain. The equations are equally valid for wood or steel side members, which are taken into account by thickness and dowel-bearing strength parameters. The equations are also valid for various load-to-grain directions, which are taken into account by the K_θ and F_e parameters. The dowel-bearing strength of the wood members is determined from tests that relate species specific gravity G and dowel diameter to bearing strength (Wilkinson 1991). Empirical equations for bolt parallel- and perpendicular-to-grain bearing relationships are

$$F_{e//} = 77.25G \qquad F_{e\perp} = 212G^{1.45}D^{-0.5} \quad (5)$$

and these expressions determine the design connection load at a dry condition. This condition is assumed to have an average MC of 15% with a maximum value of 19%. If moisture conditions are greater than 19%, the minimum design load, which is determined by the appropriate yield expressions, is modified by a wet service factor.

Wet service factors

The MC effect of wood in mechanical connections is recognized in the 1997 NDS and the 1996 LRFD. Wet service factors, denoted by C_M in these design codes, serve as adjustments to connection allowable design values based on the conditions of the wood in a connection at the time of fabrication and while in service. Wet service factors for connections are defined in one of two states: dry (19% MC or less) and wet (19% MC or more). These factors were simplified in the 1997 NDS. Prior to that date, the NDS defined three wet service conditions for the more common fasteners. The additional state was partially seasoned, defined as MC between 19% and 30%.

McLain (1997) concluded that the historical basis for wet service factors for wood screws and lag screws, which are identical to those for bolts, is loosely tied to Cockrell's (1933) results. Although the exact historical basis for the wet service factor for laterally loaded common nails is unknown, it is believed to be based on data obtained from connection tests conducted at the USDA Forest Service, Forest Products Laboratory (FPL) prior to publication of the first edition of the Wood Handbook (USDA 1935). In that publication, reference is made to "data available" from lateral connection tests comparing green with seasoned wood. Consequently, when wet or partially seasoned wood is used, adjustments are made to the allowable values of designed connections and not to the properties (i.e., dowel-bearing strength values) associated with the wood in the connection.

Dowel-bearing strength

Dowel-bearing strength values in the NDS and LRFD are based on research conducted by Wilkinson (1991). His research addressed the effects of specific gravity, dowel diameter, and loading direction but did not address MC effects or the wet service factor. All specimens for Wilkinson's bolt dowel-bearing strength tests were between 10% and 12% MC.

In bolt and nail head embedment tests, Wilkinson (1971) found that as MC increased, the load at 1.27-mm (0.05-in.) embedment was lower, yet values of maximum load remained constant. His results showed an approximate 40% reduction in load at 1.27-mm (0.05-in.) embedment for 19.1-mm (0.75-in.) bolts between specimens at 10% and 25% MC, whereas only about half that percentage of reduction was found for 3.76-mm (0.148-in.) (10d) nails.

Ehlbeck (1979) thoroughly discusses prior research on the effects of MC on embedding (dowel-bearing) strength. (Ehlbeck also discusses empirical relationships developed between embedding strength and ultimate compression strength, which is addressed later in this paper). One of the earliest reports was by Fahlbusch (1949), who defined a relationship between "peripheral hole strength" (i.e., dowel-bearing strength) and "dampness of wood" for both solid ("grown") and processed wood. The relationship he developed for solid wood (Eq. [6]) using pine, linden, and ash with a 12-mm bolt is valid between MC of 5% and 30%. In the following equation, 12% MC was used as the basis. (Eqs. [6], [7], and [8]) are presented in their original units.)

$$F_{e_m} = \frac{26F_{e_{12}}}{m + 14} \tag{6}$$

where $F_{e_{12}}$ = peripheral hole strength at 12% MC in N/mm², and F_{e_m} = peripheral hole strength at m, which is MC in percent.

More recently, Koponen (1991) developed a two-part linear model to describe the effect of MC on embedding strength (Eq. [7]) for 12- to 20-mm-diameter bolts. Conducting tests on Finnish spruce that had an average oven-dry specific gravity of 0.48, Koponen varied MC between 9% and green and arrived at the following equation, in which $r^2 = 0.82$:

$$\begin{aligned} F_e &= 46.7 - 1.35m \quad \text{when } m < 22.5\% \\ F_e &= 16.5 \quad \text{when } m > 22.5\% \end{aligned} \tag{7}$$

where F_e = embedding strength in N/mm², and m = moisture content in percent.

The intersection MC, M_p, identified by Wilson (1932) and discussed by Green and Kretschmann (1994), is the point at which the straight line approximation of the green data intersects with the straight line approximation of the dry data. At MC greater than the M_p value (what Wilson termed the apparent fiber saturation point), no further change in mechanical properties occurs. As Eq. (7) indicates, Koponen found M_p = 22.5% for embedding strength in Finnish spruce, which is below Wilson's value of 27% for red and Sitka spruce. Green and Kretschmann identified M_p = 23% for clear Southern Pine, which compares favorably with the 21% found by Wilson.

Winistorfer (1994) identified a significant MC effect on the dowel-bearing strength of two softwoods using 3.33-mm- (0.131-in.-) diameter smooth shank nails. Although the tests were conducted as auxiliary tests to validate yield theory for small-diameter nails, he found that the dowel-bearing strength values in Southern Pine and Spruce–Pine–Fir were higher at 6% MC than at 24% MC, by about 56% and 72%, respectively.

Ultimate compression strength

Trayer (1932) found that the proportional limit parallel-to-grain bearing stress of softwoods using bolts with length to diameter (L/D) ratios less than 2 was approximately 64% of the parallel-to-grain compression strength of matched samples for MC ranging between 10% and 14%. Trayer's report stated only that the wood was "seasoned." Original data from these tests, retrieved from FPL archives, showed that the MC of the specimens ranged between 10% and 14%.

Kuipers and Vermeyden (1965) developed the following empirical formula (Eq. [8]) to relate the "crushing strength at the face of a fastener hole" (i.e., dowel-bearing strength) and the compression strength of 564 matched pairs of European spruce at 12% MC, using a nail with diameter of 6.7 mm (0.263 in.). With $r^2 = 0.78$, the formula is

$$F_e = 0.6F_c + 6 \tag{8}$$

where F_e = embedding strength in N/mm², and F_c = compression strength in N/mm².

Larsen and Sorensen (1973) found that the relationship between dowel-bearing strength and compression strength in Nordic spruce and fir is dependent on the diameter of the fasteners used. For nails and bolts with diameters more than 6.1 mm (0.24 in.), the relationship for dowel-bearing strength parallel to grain is

$$F_e \approx 0.7F_c \tag{9}$$

MATERIALS

Group 1: Clear Southern Pine

The dowel-bearing strength of clear Southern Pine lumber was determined using a 12.7-

TABLE 1. *Average dowel bearing strength (DBS) of Group 1 (clear southern pine) specimens along with moisture content (MC), specific gravity, coefficient of variation (COV), and number of offset values.*

No. of specimens	Avg. MC (%)	MC range (%)	Avg. specific gravity[b]	Avg. dowel-bearing strength (MPa)	COV	No. of 5% offset values used in DBS calculations
44	4.1	3.8–4.3	0.531	45.9	0.17	5
40	6.5	6.0–6.8	0.53	42.1	0.19	11
33[a]	12.2	9.9–13.5	0.54	33.1	0.18	13
42	19.1	18.1–20.3	0.52	28.4	0.14	29
43	102.3	39.5–149.2	0.53	19.5	0.15	41

[a] Five specimens culled because of testing equipment problems.
[b] Specimen volume was adjusted to 12% MC using equations given in ASTM D2395 (ASTM 1998b).

mm- (0.5-in.-) diameter rod (Table 1). The specimens were end-matched sections of those from which strength properties were previously determined (Green and Kretschmann 1994). Green and Kretschmann generated five specific-gravity-matched source lumber sets by a random stratified technique. Five sets of matched source material (approximately 40 specimens each) were placed into conditioning chambers of specified temperature and relative humidity (RH) to achieve a target equilibrium moisture content (EMC). The following environmental conditions were used:

4% EMC [32°C (90°F), 20% RH]

6% EMC [27°C (80°F), 30% RH]

12% EMC [23°C (74°F), 65% RH]

19% EMC [27°C (80°F), 90% RH]

The fifth set was saturated by water soaking under vacuum. To prevent excessive stain and the possibility of decay, the saturated material was stored in sealed bags at a cold room temperature of 2°C (36°F) and 82% RH. After achieving the target EMC, source material was fabricated to final specimen dimensions and holes were drilled. Then specimens were returned to the conditioning room for storage until testing. Prior to testing, the specimens were removed from the cold room, still sealed in bags, and allowed to warm to room temperature.

Each specimen was 20.3 mm (0.8 in.) thick, 38.1 mm (1.5 in.) wide, and 88.9 mm (3.5 in.) long, with the long axis of the specimen oriented parallel to the grain. A 12.7-mm- (0.5-in.-) diameter hole was drilled into one end of each piece; then the piece was cut so only half of the hole remained. All specimens were then placed in their respective conditioning rooms until removed for testing. A 12.7-mm- (0.5-in.-) diameter smooth shank rod was used to apply load through the machine load-head to each specimen (Fig. 1).

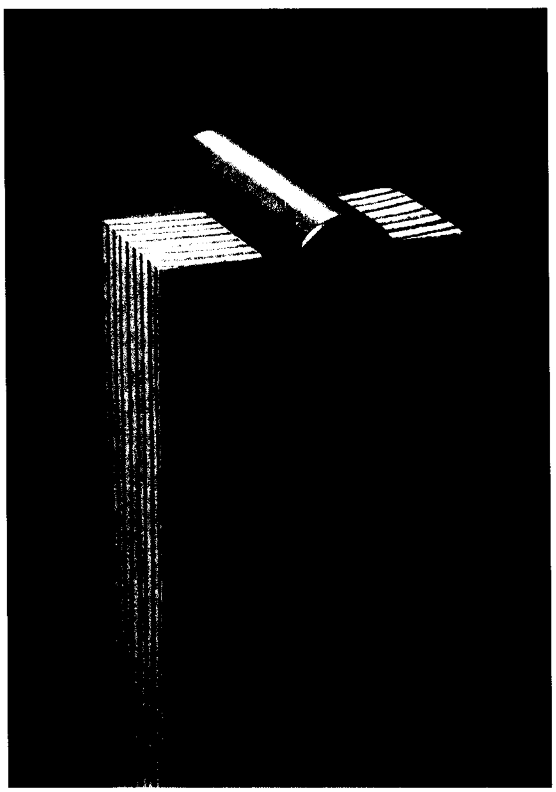

FIG. 1. Dowel-bearing specimen with 12.7-mm (0.5-in.) diameter rod from Group 1 tests (M94 0123-10).

TABLE 2. *Average dowel-bearing strength of Group 2 specimens along with average moisture content (MC), specific gravity, coefficient of variation (COV), and ratio of dry to wet dowel-bearing strength (DBS).*

NDS[a] species grouping	No. of specimens	Avg. MC (%)	Specific gravity[b]	Avg. dowel-bearing strength (MPa)	COV	Ratio of dry/wet DBS
Douglas Fir-Larch	31	6.4	0.53	56.7	0.14	
	36	23.9	0.48	33.2	0.07	1.70
	24	6.4	0.50	51.6	0.11	
Southern Pine	24	24.0	0.47	33.1	0.13	1.56
	24	6.5	0.50	41.9	0.07	
Spruce-Pine-Fir	24	28.2	0.38	24.2	0.10	1.72

[a] NDS, National Design Specification.
[b] Oven-dry weight/volume at time of test.

Group 2: Southern Pine, Douglas Fir–Larch, and Spruce–Pine–Fir

Dowel-bearing strength tests were conducted as part of a complementary project (Winistorfer 1994; Winistorfer unpublished data). Three matched specimens from each of 56 nailed connections made of three softwood groups (Southern Pine, Douglas Fir–Larch, and Spruce–Pine–Fir) were obtained after lateral joint testing was complete (Table 2). Specimens were conditioned in two MC environments: 6% and 20+%. Dowel-bearing specimens were 38.1 mm (1.5 in.) thick, 88.9 mm (3.5 in.) wide, and 76.2 mm (3 in.) long (a nominal 2 by 4, 3 in. long). A 3.18-mm- (0.125-in.-) diameter half-hole was routed into the cross section in the 38.1-mm (1.5-in.) dimension. A smooth shank, 3.33-mm- (0.131-in.-) diameter nail was placed in the half-hole for testing (Fig. 2).

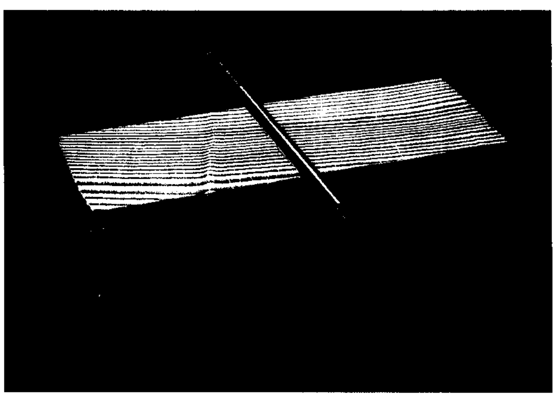

FIG. 2. Dowel-bearing specimen with 3.33-mm- (0.131-in.-) diameter nail from Group 2 tests (M94 0123-54).

METHODS

Testing

For Group 1 specimens, the 12.7-mm- (0.5-in.-) diameter rod was placed in the half-hole of the specimen. A 3.33-mm- (0.131-in.-) diameter nail was the fastener used in the related tests of Group 2. Load was applied parallel-to-grain at a crosshead speed of 0.25 mm/min (0.01 in/min) along the entire length of the fastener in accordance with standard methods (ASTM 1998c). Deflection of the testing machine crosshead was measured with a linear variable differential transformer (LVDT). This deflection was judged to be equal to that of the displacement of the fastener into the wood specimen. Continuous load and deflection data were recorded with a computer.

Immediately prior to testing Group 1 specimens, the weight of each was measured and recorded. After testing, the oven-dry method (ASTM 1998b) was used to determine MC at time of test for each specimen. Specific gravity and other strength data were already available for matching specimens (Green and Kretschmann 1994). Specific gravity values were calculated using oven-dry weight and volume adjusted to 12% MC. Similar methods were used to determine the MC of Group 2 specimens after the dowel-bearing tests were complete. Specific gravity of Group 2 specimens was calculated using oven-dry weight and volume before drying (ASTM 1998b).

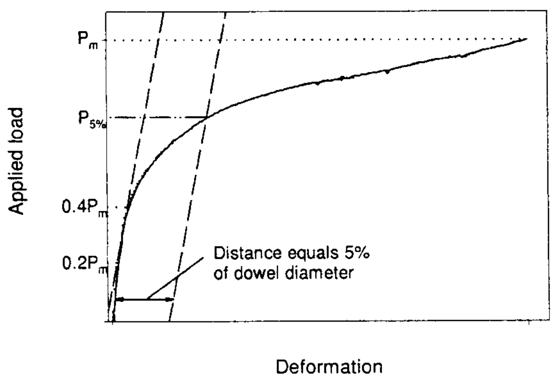

FIG. 3. Typical load-deformation curve and definition of yield load (P, load; P_m, maximum load).

Analysis

The 5% diameter offset yield load (referred to as yield load henceforth) was determined for each specimen and is the parameter used to define connection yield in 1991 NDS methods. To obtain the yield load (Fig. 3), a linear regression analysis was conducted on the data between 20% and 40% of the maximum load (P_m) to approximate initial slope of the load-deformation curve. The slope was then offset an amount equal to 5% of the diameter of the fastener used in testing [0.635 mm (0.025 in.) for Group 1 tests and 0.166 mm (0.00655 in.) for Group 2 tests]. The point of intersection of the offset slope line and the load-deformation curve determined the yield load, or if the offset line did not intersect the load-deformation curve, the maximum load of the test was used as the yield load. Dowel-bearing strength values were calculated by dividing yield load by the product of fastener diameter and loaded length of the fastener.

RESULTS

A load-deformation curve (Fig. 3) was obtained for each of the dowel-bearing tests. For most of the specimens in dry conditions (4%, 6%, and 12% MC), the 5% offset line did not intersect the load-deformation curve; therefore, maximum loads were used for the yield load. When the 5% offset line did intersect the load-deformation curve in the dry specimens, it did so after a maximum had been achieved. Table 1 indicates the average specific gravity, average yield, and coefficient of variation along with the number of 5% offset values used in the yield strength calculation. As MC increased, the use of the 5% offset line intersection point as the yield load increased. Only in high MC specimens (19% and green) did the load-deformation curve exhibit a more gradual failure, resulting in the 5% offset line intersecting the load deformation curve below the maximum load. In most cases, the Group 1 clear Southern Pine specimens failed by bearing or achieved maximum load approximately 3 to 4 minutes into each test.

For Group 2 tests of Douglas Fir–Larch, Spruce–Pine–Fir, and Southern Pine, specimens failed approximately 2 minutes into each test. All Group 2 specimens failed in bearing, with the exception of five Douglas Fir–Larch samples and one Spruce–Pine–Fir sample at 6% MC. In these six samples, failure occurred abruptly due to cracking of the specimen under the fastener during loading, most likely caused by tension perpendicular-to-grain under the dowel. This type of failure at low MC has been observed previously in Douglas Fir (Suddarth 1990).

Approximately 20% of Group 1 specimens at 4% and 6% MC appeared to fail abruptly just after the maximum test load was reached. It is possible that the combination of a relatively large fastener (12.7-mm-diameter bolt) and short specimen (88.9 mm) at relatively low MC contributed to this type of failure. As a result of these failures, an auxiliary test was conducted to determine if the specimen length of 88.9 mm (3.5 in.) was sufficient to induce dowel bearing rather than parallel-to-grain cracking failures.

Three matched samples of Southern Pine were tested at three different MC levels using a 12.7-mm- (0.5-in.-) diameter rod for a total of 18 tests. For each MC level, two specimen lengths were tested, 88.9 mm (3.5 in.) and 139.7 mm (5.5 in.). Dowel-bearing failures were observed, and results showed that specimen length had no effect on dowel-bearing

TABLE 3. *Average maximum dowel-bearing strength (DBS) of extra specimens using 12.7-mm-diameter rod.*

	88.9-mm length		139.7-mm length		
Moisture content (%)	DBS (MPa)	COV	DBS (MPa)	COV	Ratio of 139.7/88.9 mm DBS
4	43.7	11.2	40.5	13.2	0.93
12	42.2	5.0	43.4	5.2	1.03
19	34.0	4.5	33.4	7.1	0.98

strength (Table 3). Statistical analysis of the results found no practical difference between the dowel-bearing strength of the two sets of samples at any MC.

ANALYSIS AND DISCUSSION

Moisture content and dowel-bearing strength

Group 1 data, with its wide range of MC, provided the most reliable means of modeling how dowel-bearing strength was affected by MC. Group 2 data were then used to determine how well the model described the MC effect on dowel-bearing strength across a variety of wood species groupings commonly used for construction in the United States.

Figure 4 shows the data points for Group 1 clear Southern Pine with separate linear regression models for the 4% through 19% MC groups and the green data. Table 1 contains average dowel-bearing strength values with associated coefficients of variation for each MC level of these data sets. Figure 5 illustrates the MC versus dowel-bearing strength relationship for each of the species groupings in Group 2. Lines connect the average dowel-bearing strength for each species grouping at 6% and 20+% MC. The average dowel-bearing strength and MC with associated coefficients of variation for each Group 2 species grouping are found in Table 2.

In Fig. 4, the plot of Group 1 data shows a linear relationship between MC and dowel-bearing strength F_e represented by two regression lines. Actual residuals of each set were analyzed and found to be normally distributed. The regression lines, one for dry data (i.e., 4% to 19% MC) and one for the green specimens, result in an intersection MC of M_P = 25.3%, which compares favorably with the 23% MC found by Green and Kretschmann for clear Southern Pine. The regression equation for the dry portion of the data is described as follows, with r^2 = 0.52:

$$F_e = 49.95 - 1.186m \qquad (10)$$

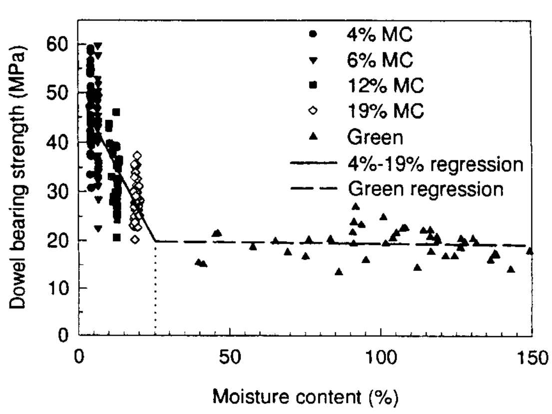

FIG. 4. Moisture content (MC) versus dowel-bearing strength for Group 1 specimens at different moisture contents with regression models.

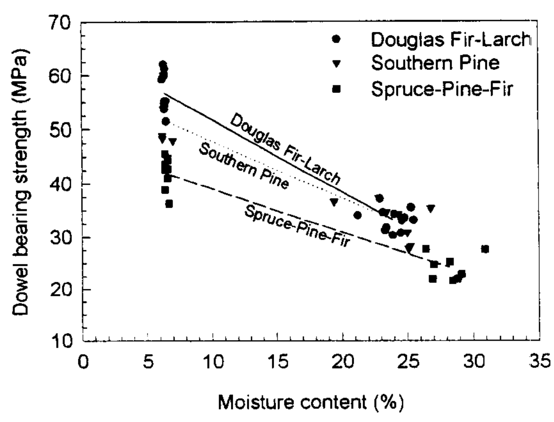

FIG. 5. Moisture content versus dowel-bearing strength for Group 2 data; lines connect average values at each moisture content level for species group listed.

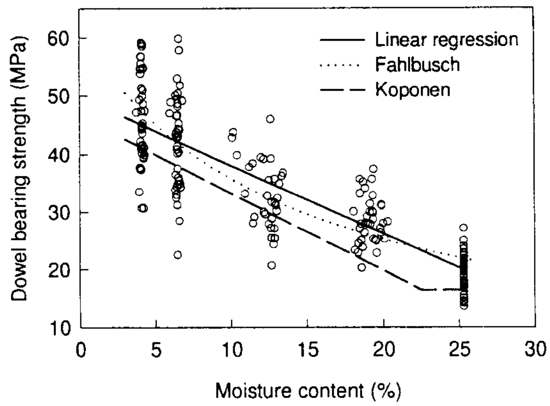

FIG. 6. Moisture content versus dowel-bearing strength model (Eq. [10]) compared with relationships developed by Fahlbusch (Eq. [7]) and Koponen (Eq. [6]).

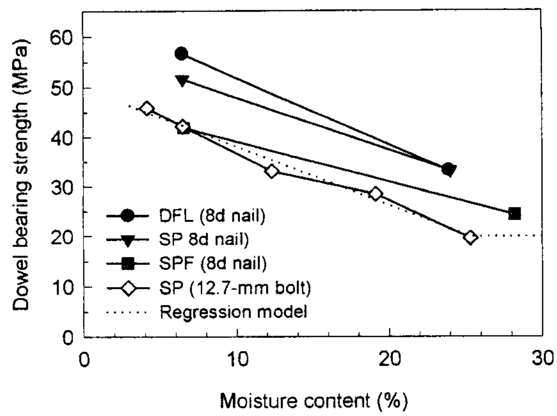

FIG. 7. Moisture content versus dowel-bearing strength for combined data from tests of Group 1 and 2 (Winistorfer 1994) and regression model (DFL, Douglas Fir–Larch; SP, Southern Pine; SPF, Spruce–Pine–Fir; 8d = 3.33-mm (0.131-in.) diameter).

where F_e = dowel-bearing strength in MPa, and m = moisture content in percent.

Equation (10), Koponen's relationship (Eq. [7]), and that developed by Fahlbusch (Eq. [6]) are plotted in Fig. 6, and all show good comparisons with the Group 1 data of this project. Saturated dowel-bearing results were shifted to the intersection MC of 25.3% because strength properties do not change above this value and because the MC dowel-bearing strength behavior between 25.3% and 4% MC is easier to observe. Comparing the linear regression model (Eq. [10]) with Group 2 data from Fig. 5 illustrates that the regression model appears to describe the general trend of decreasing dowel-bearing strength with increasing MC fairly well (Fig. 7). Although the slope of the Spruce–Pine–Fir relationship is shallower than that for the Douglas Fir–Larch or either Southern Pine group, the near-equal slope of the lines of each of the data sets suggests that MC affects dowel-bearing strength of these three species groupings in similar ways.

The average values of Group 2 samples at 6% MC are higher than might be expected given that the specific gravities of the Group 2 Douglas Fir–Larch and Southern Pine specimens are approximately equal to that of the Southern Pine from Group 1. This may be attributed to a diameter effect, given that Group 1 had a 12.7-mm- (0.5-in.-) diameter rod and Group 2 had a 3.33-mm- (0.131-in.-) diameter nail. Wilkinson (1991) found that there was a significant diameter effect for bolts but that the effect for nails was insignificant.

A general F-test was used to check the homogeneity of the slopes by comparing the reduced sum of squares between two models. A single linear model that preserved individual regression relationships for each data set was developed and compared with a reduced linear model that maintained individual intercepts for each data set but had a common slope (Weisberg 1985, pp. 178–185). Of the four data sets, only Group 1 had a definite M_p value. For Group 2, published M_p values were used; 24% for Douglas-fir–Larch, 21% for Southern Pine, and 25% for Spruce–Pine–Fir (Green and Evans 1989). These are similar to clear wood M_p values determined by Wilson (1932) for Douglas-fir, Southern Pine, Sitka spruce, and red pine. Moisture content values that exceeded the specific species M_p values were changed to the published value. Five, seven, and eight points were shifted for the Douglas-fir, Southern Pine, and Spruce–Pine–Fir data, respectively. The F-test statistic for testing the commonality of slopes was 1.433, which is smaller than the 5% critical F value of 2.668; therefore, it is concluded that the slopes of the individual data sets are both visually and statistically similar. The change of dowel bearing strength with MC is independent of both the species and dowel diameter for these tests.

Wet service factors in the NDS and LRFD adjust 15% MC dry design values to a MC above 19%, typically taken to be 20% MC (AF&PA 1997; ASCE 1996; ASTM 1998a). With the 20% MC level as a base, the following multipliers, generated from the model (Eq. [10]), can be used to adjust dowel bearing strength to listed MC levels:

$$\text{15\% MC:} \quad F_{e@15\%} = 1.23(F_{e@20\%}) \quad (11)$$

$$\text{12\% MC:} \quad F_{e@12\%} = 1.36(F_{e@20\%}) \quad (12)$$

$$\text{6\% MC:} \quad F_{e@6\%} = 1.63(F_{e@20\%}) \quad (13)$$

$$\text{4\% MC:} \quad F_{e@4\%} = 1.72(F_{e@20\%}) \quad (14)$$

With values from Table 2, ratios of dowel-bearing strength values at 6% to those at 20+% MC from Group 2 are 1.69 (Douglas Fir–Larch), 1.56 (Southern Pine), and 1.73 (Spruce–Pine–Fir), which compares reasonably with the 6% to 20% MC ratio of 1.63 for clear Southern Pine generated from Eq. (10). The model (Eq. [10]) could be used to generate similar factors at other MC levels.

As the wood building design community moves toward a load and resistance design philosophy, there is a need to quantify the underlying strength distributions. In this study, we used maximum likelihood estimators to examine three types of distributions: normal, lognormal, and two-parameter Weibull for the 5% diameter offset strength. These distributions were chosen because they are typically used to classify mechanical response in wood and wood-based materials. Chi-squared, Anderson-Darling, and K-S tests were performed to evaluate the goodness-of-fit of these distributions to the data. Offset strength values were adjusted to an average MC level of the data set by Eq. (10) before conducting the distributional analysis. Figure 8 shows the specific gravity histogram and 5% diameter bearing strength histogram for bolts at 12% MC with the normal, lognormal, and Weibull distributions superimposed on the figure. All distribution parameters found by the likelihood estimators along with the goodness-of-fit estimates are listed in Table 4 for each MC level. Based on the χ^2 values, lognormal probability distribution seemed to successfully model the 5% diameter bearing strength for each MC level except the saturated condition.

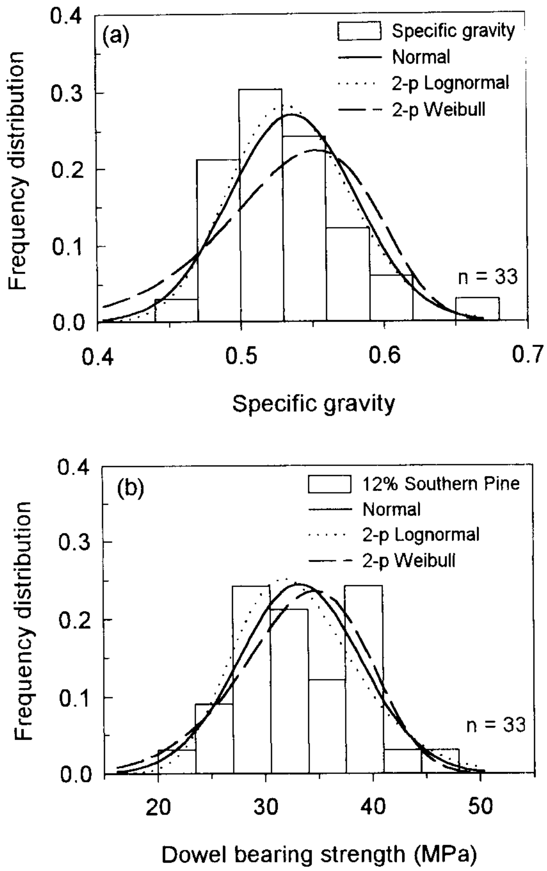

FIG. 8. Histograms for (a) specific gravity of Southern Pine specimens at 12% MC and (b) bolt dowel-bearing strength at 12% MC in Southern Pine (n = number of specimens).

Bolt design implications of moisture content

Both the NDS and LRFD standards apply a constant wet service factor, $C_M = 0.7$, to the calculated design capacity for wet use. This factor, used to adjust 15% MC design values

TABLE 4. *Five percent diameter offset stress probability distributions for Group 1 bolts.*

Moisture content	Distribution[a]	Scale parameter (α)	Shape parameter (β)	χ^2	KS	A-D
4%	Normal[b]	45.877	56.694	6.909	0.1030	0.4873
	Lognormal	3.812	0.0282	2.545	0.0983	0.4079
	Weibull	49.079	6.811	6.182	0.1249	0.6735
6%	Normal	42.136	63.299	7.200	0.0923	0.2811
	Lognormal	3.722	0.0396	5.200	0.1227	0.4622
	Weibull[b]	45.405	5.907	11.200	0.0901	0.2803
12%	Normal	33.218	31.333	5.000	0.1058	0.3367
	Lognormal[b]	3.489	0.0296	3.545	0.1261	0.3466
	Weibull	35.582	6.465	5.000	0.0943	0.3695
19%	Normal	28.412	17.049	1.405	0.0658	0.1351
	Lognormal	3.336	0.0216	1.405	0.0553	0.1221
	Weibull[b]	30.214	7.413	2.162	0.1005	0.3340
Saturated	Normal[b]	19.481	8.681	4.814	0.0816	0.1517
	Lognormal	2.958	0.0238	4.442	0.1118	0.3017
	Weibull	20.741	7.082	2.209	0.0687	0.2547

[a] Normal distribution

$$f_x(x) = \frac{1}{\beta\sqrt{2\pi}}\exp\left[-\left(\frac{x-\alpha}{\sqrt{2}\beta}\right)^2\right]$$

Lognormal distribution:

$$f_x(x) = \frac{1}{x\beta\sqrt{2\pi}}\exp\left[-\left(\frac{\ln x-\alpha}{\sqrt{2}\beta}\right)^2\right]$$

Weibull distribution:

$$f_x(x) = \frac{\alpha}{\beta^\alpha}x^{\alpha-1}e^{-(x/\beta)^\alpha}$$

[b] Best fitting distribution for specific gravity.

to a green (MC > 19%) condition, was carried over from the previous design's empirical-based lateral strength provisions. Currently, wood connections are designed according to the yield model that uses two material parameters, dowel-bearing strength and fastener-bending yield strength, to determine capacity. Of these two material parameters, only dowel-bearing strength is affected by MC. If the bolted connection design is governed by dowel-bearing strength (Modes I and II), the influences of MC would be greater. Whereas, if the bolted connection design is governed by the interaction of dowel-bearing and nail-bending strength (Mode III and IV), the influence of MC would be less.

To compare the effectiveness of the current connection wet service factor, yield-theory-derived moisture effects will be compared with the constant factor $C_M = 0.7$. For a 12.7-mm bolted connection, the wet (MC = 20%) and dry (MC = 15%) joint design capacity was calculated assuming the following material properties as given by the NDS: F_e = 400 MPa for steel side plates, and F_{yb} = 310 MPa (AF&PA 1997). Dry parallel-to-grain Southern Pine dowel-bearing strength was calculated as F_e = 42.4 MPa by Eq. (5) using a specific gravity of 0.55, and wet Southern Pine dowel-bearing strength was calculated to be 34.5 MPa by Eq. (11) with the dry value. The ratio of wet capacity (Z_{wet}) to dry capacity (Z_{dry}) of single and double shear connections with 6.4-mm steel side plates was calculated for various bolt slenderness ratios, t_m/D, where t_m is main member thickness and D is the bolt diameter (Fig. 9a) using Eqs. (1) through (4) and a similar set for single shear connections. For a single shear joint with steel side plates, both the dry and wet connections experience Mode I, II, and III failures resulting in three distinct regions with steep transitions between the regions. These transition regions represent cases where the failure modes are different be-

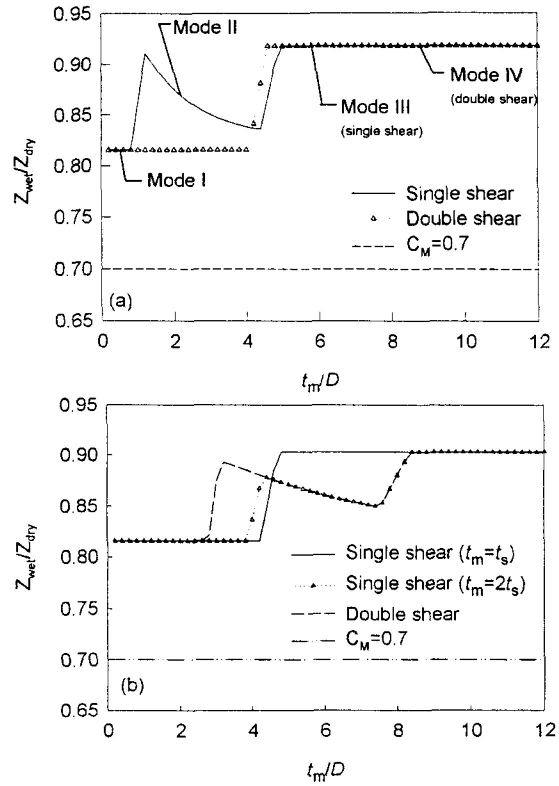

FIG. 9. Effect of moisture content on the design of bolted connection using yield theory (a) steel side plates (b) wooden side members (Z, connection capacity; C_M, constant wet service factor; t_m, main member thickness; *D*, bolt diameter; t_S, side member thickness).

tween the wet and dry joint. For a double shear joint with steel side plates, there are only two modes of failure, I and IV.

Ratios of wet capacity to dry capacity of single and double shear connections with wood side members were calculated for various bolt slenderness ratios (Fig. 9b). For single shear, two side member thicknesses were used, $t_s = t_m$ and $t_s = t_m/2$, and for double shear, the side member was half the main member thickness. Figure 9b, shows that the trends were similar between joints with steel side plates and those with wooden side members but that changes in ratios of wet to dry capacity occurred at different slenderness ratios. For single shear with wood side plates, Mode IV governed joint design for large bolt slenderness ratios instead of Mode III for the joints with steel side members. In both single and double shear scenarios, the greatest effect of moisture is seen for low bolt slenderness ratios that are dependent only on dowel-bearing strength, Mode I or II failures. As the slenderness ratios increased, the effect of MC decreased. This is the influence of the fastener-bending strength, which is not affected by MC.

Figure 9 shows that the current wet service adjustment is more restrictive than ratios calculated by changing the dowel-bearing input values in the yield theory expression, and the effect of MC on joint capacity is not constant across the range of bolt slenderness ratios investigated.

Although NDS design methods require that the wet use factor be applied to the calculated design value of a connection, the limited data and applications of the design connection yield expressions of this study suggest that moisture adjustments could instead be applied to the wood property of dowel-bearing strength only.

Dowel bearing strength compared with compression strength

Since dowel-bearing strength and ultimate compression strength, each applied parallel to grain, both measure wood's resistance to crushing, it would follow that they should be positively correlated. This belief is verified by comparing dowel bearing strength obtained from these tests with the ultimate compression strength obtained from matching specimens (Green and Kretschmann 1994). Figure 10 shows the linear regression derived from all the matched Group 1 samples. Analysis indicated a good correlation, with $r^2 = 0.76$, and produced normally distributed residuals. Equation (15) describes this relationship, with both dowel-bearing strength F_e and ultimate compression strength F_c in MPa:

$$F_e = 0.438F_c + 11.897 \qquad (15)$$

Included in Fig. 10 are the linear relationships developed by Kuipers and Vermeyden (1965) and Larsen and Sorensen (1973). Table 5 pre-

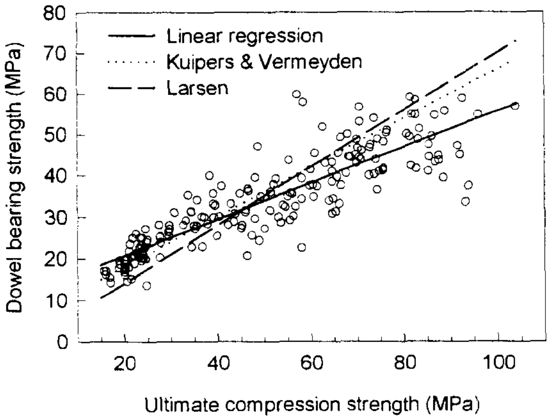

FIG. 10. Ultimate compression strength versus dowel-bearing strength using linear regression model (Eq. [15]) compared with Kuipers and Vermeyden (1965) and Larsen and Sorensen (1973) (data from experiments and from Green and Kretschmann (1994)).

sents data from Group 1 specimens that result in a ratio of dowel-bearing strength to ultimate compression strength in the 60% to 65% range for dry material (15% MC or less), which compares favorably with ratios from the three studies discussed earlier: Trayer (64%), Kuipers and Vermeyden (60%), and Larsen and Sorensen (approximately 70%).

However, as shown in Table 5, this ratio increases to approximately 90% at MC of 19% and above. It is clear that the relationship from Eq. (15), with a coefficient of 0.438, has a lower slope than that in the previous three studies. However, both Kuipers and Vermeyden (1965) and Larsen and Sorensen (1973) tested low density European softwoods with compression strengths between 21.8 and 43.8 MPa, whereas Trayer used control specimens with compression strengths between 29.4 and 43.4 MPa. Their data cover only the lower third of the range of compression strength in this study and are limited to relatively dry material. Therefore, Eq. (15) provides a more robust relationship between dowel-bearing strength and compression strength than do the other three studies because it covers a wide range of compression strengths in dry to green material.

TABLE 5. *Ratio of dowel-bearing strength (DBS) to ultimate compression stress (UCS).*

Avg. MC (%)	Ratio of DBS/UCS	COV (%)
4.1	0.60	0.163
6.5	0.63	0.221
12.2	0.65	0.171
19.0	0.88	0.123
Green	0.91	0.121

CONCLUSIONS

Dowel-bearing strength values are needed to determine the design strength of wood connections using yield theory methodology. Since MC level affects other strength properties of wood, it is possible that dowel-bearing strength, a measure of wood's resistance to crushing under a fastener, could be affected by varying levels of MC as well.

With the dowel-bearing strength values obtained from two groups of softwood specimens, the data suggest the following:

- Dowel-bearing strength increases with decreasing MC, much like other wood properties, and an empirical linear model is presented relating the two (Eq. [10]).
- The relationship between dowel-bearing strength and MC is independent of species type for the three tested species.
- The relationship between dowel-bearing strength and MC is independent of fastener diameter for the two diameters tested.
- Adjustments to account for strength reducing factors related to MC of connections could be applied to the dowel-bearing strength of the wood rather than the design value of the connection.
- Parallel-to-grain dowel-bearing strength is highly positively correlated with ultimate parallel-to-grain compression strength and is estimated by a linear regression relationship (Eq. [15]).

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