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Dowel-Nut Connection in Douglas-fir Peeler Cores

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Abstract

As part of an effort to encourage more efficient use of small-diameter timber, the Forest Products Laboratory cooperated with Geiger Engineers in a study of the structural properties of Douglas-fir peeler cores and the efficacy of a "dowel-nut" connection detail for application in the design of a space frame roof system. A 44.5-mm- (1.75-in.-) diameter dowel-nut connector was found to be economically feasible at a design capacity of 44.5 kN (1.0×10^4 lbf) for a 127-mm- (5-in.-) diameter Douglas-fir peeler core. Variables that affect joint strength and failure mode are location of the dowel nut, wood moisture content, presence of reaction wood, and grain angle orientation with respect to force vectors. The results of this study provide a basis for deriving design properties for peeler core structural application in a space frame roof system and the foundation for establishing a database to support small-diameter timber design and construction standards.

Keywords: Dowel nut, small-diameter timber, Douglas-fir, design properties

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Introduction

Structural application of small-diameter timber is currently limited by conventional construction standards. The round tapered shape is not compatible with conventional framing and cladding methods. Round timber connections are generally custom made and their design properties are based on limited test data, making these connections expensive and their design capacity conservative.

The Forest Products Laboratory (FPL) has initiated a research program to assess uses for small-diameter timber in an effort to encourage more efficient use of this material. Research on structural applications includes the characterization of material and connection properties, processing, design of demonstration structures, and economic feasibility. The goal of this work is to encourage innovative uses in structures by providing not only the information needed to design structures but also some basis for evaluating economic feasibility.

Geiger Engineers cooperated with the FPL in a study to assess the efficacy of using Douglas-fir peeler cores, a by-product of wood veneer production, in structural applications. Geiger's interest included verification of design assumptions made in reference to guidelines noted in the *National Design Specification for Wood Construction* (ANSI/AF&PA 1997) and finding an economically feasible connection. The FPL's interest was in strengthening the technical basis necessary to support development of small-diameter timber design and construction standards.

Objective and Scope

The objectives of this study were as follows:

- To provide a basis for deriving design stresses for 127-mm- (5-in.-) diameter Douglas-fir peeler cores to be used as axially loaded elements in a space frame truss roof assembly
- To add to the limited knowledge on techniques for making more efficient use of small-diameter round timber

This paper describes test procedures and results for a very specific application. Its scope is limited to the consideration of only one joint configuration designed to resist only axial tension and the axial compressive strength and stiffness of the material. The target application assumes that tensile stresses carried by the timber will be limited by the connection. In compression, it is assumed that the critical buckling load will be the limiting factor that makes stiffness the critical issue for design.

Material

The round timbers used in this study were 127-mm- (5-in.-) diameter Douglas-fir peeler cores. A peeler core is the cylindrical piece left after veneer is peeled from a log. The growth rate of the timbers used to produce these cores ranged from 4 to 14 rings/in (1.6 to 5.5 rings/cm) (hereafter referred to as rpi). The pith was rarely centered, so it was not unusual for the wood on the outer surface to be within 8 to 10 annual rings of the pith. Joint tests were conducted using 1.8-m- (6-ft-) long specimens, and the material compression tests were conducted with members cut to a length 4 times the average diameter (or approximately 0.5 m (1.6 ft) in length). The peeler cores had a slight taper, varying in diameter by as much as 13 mm (0.5 in.) over the 1.8-m (6-ft) length of the joint test samples. Knots were relatively small because these cores were graded to meet the No. 2 lumber grade knot requirements. The cores were machined and kiln dried at FPL prior to testing.

The test connections were fabricated from relatively high yield (0.39 to 0.41 GPa (56 to 60 $\times 10^3$ lb/in^2)) steel. Each joint consisted of a "dowel nut" cut from solid, round, 31.8- to 44.5-mm- (1.25- to 1.75-in.-) diameter hot roll steel and a 19-mm- (0.75-in.-) diameter threaded rod.

Methods

Tests included the tensile capacity of the dowel-nut connection and the compressive strength and stiffness of the peeler core sections, as well as the evaluation of nondestructive test parameters useful as quality indicators. Pilot tests were conducted to gain some knowledge of joint capacity and influence of fabrication variables.

Moisture content and specific gravity (ASTM 1993a) samples were taken after the joints were tested, but prior to the compression tests. Cross sections were examined to quantify growth rate, extent of pith eccentricity, proportion of juvenile wood, and occurrence of reaction wood. Pith eccentricity was noted as an index (0 to 1) calculated as the ratio of the distance between the pith and the geometric center of the cross section and the radius. Knot size and location were also mapped for each compression sample.

Dowel-Nut Connection

The dowel-nut connection evaluated (Fig. 1) is similar to that commonly employed in "knock-down" furniture. It requires that two holes be drilled in the peeler core: one along the diameter of the peeler core and the second along the centroidal axis. The first hole is large enough to accommodate the dowel nut and is centered 254 mm (10 in.) from the end. The second hole is 25.4 mm (1 in.) in diameter—large enough to accommodate the threaded rod, which is screwed into a threaded hole in the dowel nut.

Because of the difficulty of holding a round section in the test machine, the test connections were used to mount the samples in the test machine. The joints were tested in axial tension. The threaded rods protruding from each end of the test sample were mounted to opposing heads of the test machine and in series with a 222-kN (50×10^3 lbf) load cell.

Figure 1—Dowel-nut connection detail.

Consequently, two joints were tested at one time, one on each end of the peeler core. The two dowel-nut holes on a single test sample were oriented at 90° to each other. In each case, only one joint failed, but the load–displacement characteristics were recorded for both joints.

Pilot Tests

Preliminary analysis of the dowel-nut connection in Douglas-fir suggested that these joints were capable of attaining a design load close to 44.5 kN (1.0×10^4 lbf). A total of 16 pilot test joints were fabricated and tested. The initial pilot test was conducted on green wood. After this test, the failed ends were cut off, and the joints were re-machined and re-tested in the dry condition. Moisture change from the time of fabrication to test had a negative effect on joint behavior. On the basis of these tests, we decided that all test cores should be kiln dried prior to joint fabrication because the intended application for these joints is a protected environment where the wood will equilibrate at a moisture content of 15% or less.

The predominance of compression-parallel-to-grain failures in the pilot tests motivated us to increase the diameter of the steel dowel from the 31.8-mm (1.25-in.) size used in the pilot tests to 44.5 mm (1.75 in.). We also decided to place a 12.7-mm- (0.5-in.-) wide by 0.7-mm- (0.03-in.-) thick stainless steel strap with a threaded "T-bar" tightening device (Fig. 2) just above the dowel hole and a truss plate in the end grain oriented perpendicular to the dowel-nut hole to reinforce the resistance of the core to tension-perpendicular-to-grain forces imposed by the round dowel. The clamp was tightened with a torque of roughly 67.8 N·m (50 lbf·ft). Pilot tests of the dowel-nut connection are described in detail in Appendix A.

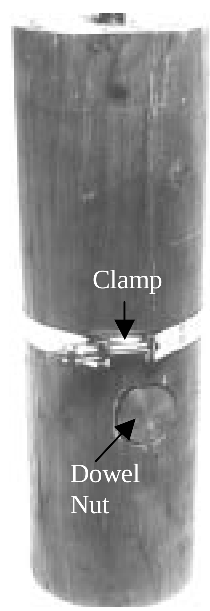

Figure 2—Steel-strap pipe clamp with threaded T-bar tightening device.

Joint Tests

A total of 32 test joints were fabricated to assess the load capacity of the dowel-nut connections. Load–deformation data were collected for each joint. A linear variable differential transducer (LVDT) with a 6.4-mm (0.25-in.) displacement range was attached to each threaded rod, with its core bearing on the end of the test timber. Load was applied maintaining a constant displacement rate of 0.254 mm/min (0.01 in./min) to attain maximum strain in 5 to 10 min.

As the test machine heads were moved apart, the displacements measured by the LVDTs were recorded and plotted against the tensile force measured by the load cell. The test continued until the load either dropped off or displacement exceeded the range of the LVDT. In all cases, the LVDT displacement range exceeded the linear load–displacement limit for the test joints so that characteristic curves were recorded to maximum serviceability limits.

After the test, the joints were inspected and disks were cut for moisture content and specific gravity determination. The joints were visually inspected to note the failure mode, any influence caused by knots or other defects, pith index, and growth rate (Fig. 3).

Compression Tests

Testing wood in the green condition has the advantage of saving the time and expense of kiln drying prior to testing. Since no machining was required for the test and we were fairly confident of the failure mode, tests on green wood (green tests) were deemed appropriate. The results of green tests can be adjusted using dry/green ratios for strength and modulus of elasticity (MOE). These ratios are published in ASTM D2555 (ASTM 1998). As the ASTM values are based on tests of small clear specimens, we deemed it necessary to check their application to peeler cores by testing both green and dry peeler cores.

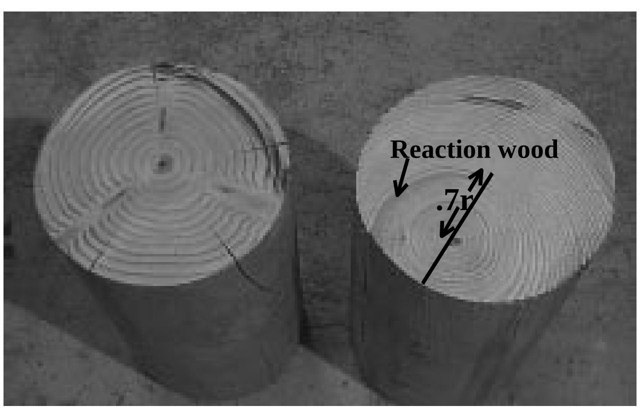

Figure 3—Comparison of growth rate to pith index and amount of reaction wood. Log on left has centered pith and no reaction wood, but a growth rate of only 4 rpi. Log on right has high pith index and reaction wood, but a more desirable growth rate of 8 rpi.

A total of 38 compression parallel-to-grain tests were conducted following procedures given in ASTM D198 (ASTM 1998) to assess member strength and stiffness. Following this standard, the tests were conducted on a length less than 17 times the radius of gyration. In the case of a round timber, the radius of gyration is 0.25 times the diameter, giving a length limit of 4.25 times the diameter. The peeler core specimens were cut to a length of 4 times their average diameter (or 0.50 m (20 in.) in length). Specimen ends were carefully cut perpendicular to their axis. The specimens were then placed in a test machine and loaded in compression parallel to grain. Load was applied using a constant displacement rate of 1 mm/min (0.04 in/min) (strain rate = 0.2%/min). Loading continued to a displacement beyond the point of maximum load. Data recorded included the load on the specimen as a function of load head movement. Load head movement was assumed to provide a measure of compressive strain over the length of the specimen up to proportional limit. The location of compression failure was noted on each test specimen.

Results

This study provided a basis for evaluating the effects of material properties, processing, and joint configuration on the load capacity of dowel-nut connections. Moisture content of the wood at the time of fabrication and characteristics of the timber in the area of the connection appeared to have a significant influence on failure mode and capacity of these connections.

Pilot Test Failures

The first round of pilot tests failed in combined compression parallel to grain and tension perpendicular to grain. There was a tendency for the dowel bearing force to push both halves of the peeler core apart, rotating about a confinement ring placed just above the dowel-nut hole. As a result, we decided to retest the joints with the confinement band further away from the dowel-nut hole and a truss plate pressed into the end of the timber to help resist tension perpendicular to grain.

By the time the second group of pilot test joints had been cut and re-machined, their moisture content had dropped from 25%–30% to 9%–20%. These drier specimens no longer exhibited excessive compression parallel to grain. Instead, they failed in shear and tension parallel to grain.

Test Joint Failure Modes

The load–displacement curves for the test joints exhibited a characteristic initial stiffening, followed by a linear portion that extended beyond 80% of maximum load. There was little

Figure 4—Shear, tension-perpendicular-to-grain, and tension-parallel-to-grain failures in test joints (left to right).

sign of the compression-parallel-to-grain deformation prevalent in the pilot tests conducted at higher moisture content. Only the last specimen tested (joint 16) showed any sign of bearing deformation parallel to grain.

The joint test results (Appendix B) exhibited three predominant failure modes (Fig. 4). The most common failure mode was combined shear and tension parallel to grain. The second most common failure mode was one in which no sign of tensile failure was evident; shear in two planes caused a section to pop out of the end. In a few instances, the failure initiated as tension perpendicular to grain, appearing as a single split in a plane parallel to and through the dowel hole. In many cases, tension perpendicular-to-grain and shear apparently acted together in splitting the timber from the dowel hole to the end. In several instances, the failure appeared as a complete tension-parallel-to-grain failure on both sides of the dowel hole with no accompanying shear. One joint with this kind of failure (joint 10) failed at a relatively low load (106.75 kN (2.4×10^4 lbf/in^2)) as a result of low quality wood around the dowel nut. On one side of the dowel, the wood was 80% juvenile and reaction wood; on the other side, the grain of 50% of the wood was oriented 30° to 45° to the load direction. Finally, one joint (joint 1) failed as a result of knots in the area of the dowel hole. Joint 1 failed at 57.8 kN (1.3×10^4 lbf/in^2) but it was not included in the analysis of results because no knots should be permitted within three diameters of the dowel hole.

Eccentric loading was noted for two test joints, joints 5 and 12. This resulted from a slight misalignment of the longitudinal hole drilled for the threaded rod. The misalignment was noticeable; the dowel nut protruded approximately 6.3 mm (0.25 in.) from one surface of the peeler core. It is difficult to assess the true effect of this eccentric load on the basis of two tests, especially when the resulting joint strength values fall at opposite extremes of the joint strength distribution.

Compression Tests

Failures for the compression tests appeared as compression wrinkles in the surface. These wrinkles were most apparent around the knots. For the sample with the lowest compressive MOE (E_c) (sample C-5-7), the failure involved shear displacement initiating at a drying check in an area of juvenile wood close to one surface. In several cases where there was a high pith index, the swivel bearing plate of the active load-head tilted to accommodate the lower E_c of the juvenile wood zone.

The compression test load–displacement curves have several distinct characteristics. They all begin with initial stiffening where a non-uniform end surface levels out. As the stresses become more uniformly distributed (>2.54-mm (>0.1-in.) displacement for 508-mm (20-in.) gauge length and 44.5 kN (1.0×10^4 lbf/in^2)), the curves become fairly linear to 50% of the maximum load. Beyond 60% of the maximum load, the curves exhibit an elastoplastic region, which then generally turns plastic beyond 3.81 mm (0.15 in.). Slopes that are measured for determination of MOE are therefore measured primarily between deformations of 2.54 and 3.81 mm (0.1 and 0.15 in., respectively) or strains of 0.5% and 0.75%.

Influencing Factors

Factors other than moisture that appeared to have a strong influence on joint performance included wood growth characteristics, processing variables, and connection details. Wood growth characteristics such as reaction wood, pith-associated wood, and angled grain can be controlled by grading. Processing variables such as drying and machining can be controlled to minimize fabrication and service problems. However, the connection details must be evaluated by testing to assure that a solution for one problem does not create other problems.

Reaction wood, pith-associated wood, and angled grain can all be detected by visual inspection. Reaction wood appears as an area of unsymmetric growth rings (see Fig. 3), readily apparent on the cross section of the timber. Pith-associated wood is present in all peeler cores. The fact that pith-associated wood is often located off-center increases the probability that it will occur in the tension zone to the side of the dowel nut unless a conscious effort is made to drill the dowel-nut hole through this wood.

Angled grain occurs as a result of knots or a bend in the tree stem that is bent down when the veneer is cut. An annual ring pattern on the surface of the peeler core consisting of concentric elliptical rings (Fig. 5) is an indicator of grain that is not parallel to the surface. This pattern occurs where several annual rings pass through the exposed surface over a short

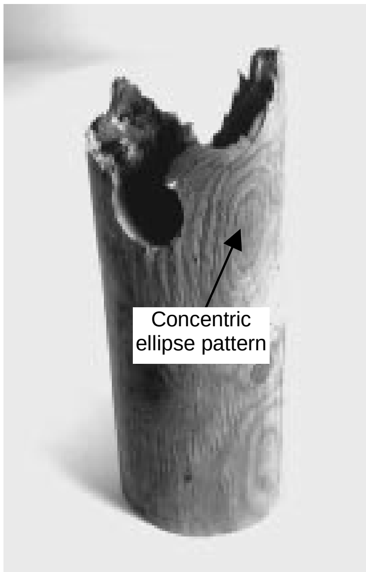

Figure 5—Concentric elliptical annual ring patterns indicate angled grain below wood surface.

length. It indicates that the tree had a slight bend or protuberance that defined the annual ring orientation at that location. The more circular the concentric rings, the steeper the localized grain just below the surface at that location.

Reaction and pith-associated wood should be avoided in areas subject to high tensile stress. This wood is weaker and less stiff than other wood and also exhibits greater longitudinal change with change in moisture content than does mature wood. When stresses are applied at an angle to the grain, strength is influenced by the proportion of wood loaded in tension perpendicular to grain. Wood loaded at this orientation is assumed to be have one-third the shear strength parallel to grain.

Problems with pith-associated and reaction wood can be minimized by proper detailing of the joint. For test joint 5, 80% of the area to one side of the dowel hole exhibited a brash tensile failure classified as reaction wood and/or pith-associated wood failure. On the other side of the dowel hole, wood fibers in 50% of the failure area were oriented at an angle at least 30° to the direction of principle stress. Angled grain was also a problem in joint 10. Joints 5 and 10 failed at approximately 106.75 kN (2.4×10^4 lbf/in^2). Joints 3, 6, and 12 also exhibited pith-associated and reaction wood, but their failure loads were 164.6 kN (3.7×10^4 lbf/in^2), 124.5 kN (2.8×10^4 lbf/in^2), and 160 kN (3.6×10^4 lbf/in^2), respectively. The difference was that the dowel holes of the stronger joints had been drilled through the pith and reaction wood areas and showed little sign of angled grain.

Six of the 16 joint test samples (joints 1, 3, 5, 6, 10, and 12) had some amount of reaction wood. Joints 5 and 10 contained significant amounts of both reaction wood and angled grain in the tensile area on either side of the dowel hole.

Processing variables include drying and machining. Dimensional change with drying and drying checks can create problems that reduce joint load capacity. Holes drilled in the wood will become smaller as the wood dries. If the steel dowel nut is inserted in a tight-fitting hole when the wood is green, the shrinkage will result in tension-perpendicular-to grain stresses in the wood in the area of the dowel, initiating a drying check in a plane parallel to that of the dowel hole. Drying checks that were oriented at an angle <45° to the dowel hole reduced the effective shear area or tension-perpendicular-to-grain area, increasing the probability of an early failure. When wood is dried prior to drilling, such stresses are not a problem. When the dowel hole is oriented to a drying check at an angle >45°, the check is less likely to contribute to a weak plane for shear- or tension-perpendicular-to-grain stress.

The joint configuration parameters that apparently exert the greatest influence on performance are dowel-nut diameter and confinement. Naturally, the larger the diameter, the greater the end grain surface area subject to compression and the smaller the area subject to tension. These two areas should be balanced slightly in favor of tension to encourage the more ductile compression failure. Confinement had a significant effect on both failure mode and load capacity. The adjustable steel confinement band placed 25.4 mm (1 in.) above the dowel-nut hole used in conjunction with a truss plate located in the end grain and oriented perpendicular to the dowel-nut hole served to reinforce the specimens against tension-perpendicular-to-grain failures. The lower incidence of bearing deformation and Poisson's effect in pushing fibers apart made the bands seem less highly stressed in the samples from the final test compared with those from the pilot tests. However, in one test (test 3), the steel band actually failed in tension, and in another test, the confinement stress that built up during the test left compression-perpendicular-to-grain bearing deformations in the surface of the timber (joint 16). In these cases, failures were predominately due to tension perpendicular to grain, implying that joint capacity would have been increased by using a second band or by pressing the metal plate connector into the end grain as was done for the pilot tests.

Analysis

The peeler cores evaluated in this study were relatively fast grown, ranging from 4 to 14 rpi. The average specific gravity was low: 0.4 compared with 0.45 generally reported for coastal Douglas-fir. The low specific gravity was most likely due to the high proportion of juvenile wood. Because juvenile wood normally predominates in the first 10 to 20 years of growth (≤8 rpi), the entire section could be assumed to be juvenile wood for a 127-mm- (5-in.-) diameter peeler core.

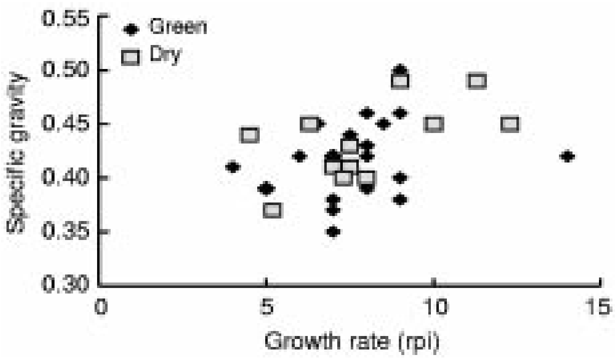

Figure 6—Increase in specific gravity with growth rate resulting from decrease in proportion of juvenile wood with age; rpi designates rings/in. 1 in. = 25.4 mm.

Cores with a higher growth rate naturally have a lower proportion of juvenile wood and therefore higher specific gravity, as indicated in Figure 6. This does not mean that slower growth in general will yield higher density. Density in mature wood is more a function of the percentage of latewood, which could easily be greater in fast-grown material than in slow-grown material.

Joint Strength

Appendix C provides an assessment of the expected maximum strength and design stress for bearing parallel to grain, tension, and shear. These assessments are based on the dowel bearing capacity of coastal Douglas-fir (ANSI/AF&PA 1997), published values for clear wood (ASTM 1998, D2555), and tensile capacity of sawn timber.

The average strength for 16 tests was 129 kN (2.9×10^4 lbf). Because two joints were used for each test, the actual sample was 32 joints. For the 16 joints that did not fail, strength was assumed to be greater than or equal to that of the joints that did fail, making the true average strength for the 32 joints greater than or equal to that determined for the 16 tests. A Student's *t*-statistic was used to estimate a 5th percentile value for joint strength assuming 31 degrees of freedom, the measured mean strength, and the sample standard deviation. The resulting value was 93 kN (2.1×10^4 lbf). Assuming a predominately tension-type failure and an adjustment of 2.1 to account for duration of load and factor of safety, the design capacity for a normal load duration would be 44 kN (1.0×10^4 lbf).

Conventional Design Values for Strength

The average strength of round timbers (ASTM 1998, Bodig and others 1986, Wolfe 1989) is generally noted to be comparable to or slightly higher than that of dimension lumber, with roughly two-thirds the variability. The reduction in variability is attributed to the fact that the wood fibers of a round timber are parallel to the surface and thus parallel to the principal stresses. The grain in a tree flows around knots and remains continuous. In lumber, on the other hand, the wood fibers are often sawn at a slight angle to the surface. The grain around knots in a piece a lumber is often discontinuous and cut at steep angles to the surface, which causes the knots to have a more deleterious effect on strength. Fiber discontinuity is often most obvious along the corners of rectangular lumber sections. This occurrence of diving grain reduces the effectiveness of the rectangular section. Design stresses derived for rectangular members should therefore be conservative when applied to a round section of comparable material quality.

Following the *National Design Specification for Wood* (NDS) (ANSI/AF&PA 1997) for wood and the strength ratio assumed for Construction-grade nominal 4- by 4-in. (standard 89- by 89-mm) lumber, the normal load–duration design capacity of the dowel-nut connection would be 44 kN (1.0×10^4 lbf) for a dowel bearing failure mode, 44 kN (1.0×10^4 lbf) for tensile failure, and 31 kN (0.7×10^4 lbf) for shear failure. However, the ASTM D2899 standard for derivation of shear design stresses for round timbers includes a strength ratio of 0.75 (Phillips and others 1985) in adjusting from small clear to full-sized round timber strength. Using this value and a coefficient of variation (COV) of 20% for round wood gives a design value of 47 kN (1.05×10^4 lbf) (App. C).

Design values derived following the ASTM recommendations appear to be in line with the value derived from the test data. The design capacity of the dowel-nut connector would be 44.5 kN (1.0×10^4 lbf) for normal load–duration shear, tension parallel to grain, and bearing. Tension perpendicular to grain, which also contributes to joint failures, could be restrained using a second clamp or a metal plate connector ("truss plate") pressed into the end grain.

The dowel bearing design for bolts in double shear, outlined in the NDS for wood published by the American Forest & Paper Association (AF&PA), gives predictions of maximum load that are close to the predicted value of 137 kN (3.1×10^4 lbf) as opposed to the measured value of 131 kN (3.0×10^4 lbf).

Joint Stiffness

The slope of the load–displacement curves for the test joints ranged from 96 to 204 kN/mm (55 to 117×10^4 lbf/in), with an average value of 150 kN/mm (856×10^3 lbf/in) and 18% COV. The linear range of the curve extended to at least 80% of the maximum load. Failures ranged from ductile parallel-to-grain compression to brittle tension failures. Brash or brittle failures involved tension-perpendicular-to-grain stresses or reaction wood. In many cases, the tension-perpendicular-to-grain stresses occurred at places where the grain was oriented at an angle to the axis as a result of the influence of a knot or other defect in the tree.

Joint Design Recommendations

The greater ductility of dowel bearing failure in compression parallel to grain makes this mode preferable to tension. The pilot test joints (App. A), which were made with green lumber, all exhibited this more ductile failure, while only one of the 16 joints tested in the dry condition did. Apparently, there would be some advantage to reducing the size of the dowel nut. This would increase the effective tensile area, reducing tensile stress at design load, and have minimal effect on the shear area. Reducing the bearing area to the point controlled by compression parallel to grain and maintaining confinement to inhibit tension-perpendicular-to-grain splitting would reduce the chance of a brash failure in the event of an unpredicted overload.

Compression Tests

Compressive strength and MOE were measured under both green and dry conditions. All test results were adjusted to 12% by interpolation of the ASTM D2555 dry/green (12%/30%) ratios (1.99 for stress and 1.27 for E_c). These results were compared using a *t*-test for mean difference, and the dry/green ratios were checked using least squares linear regression.

The ultimate compressive stress (UCS) for specimens tested at moisture content exceeding 20% averaged over 21 MPa (3.1×10^3 lb/in^2), with 11% COV. Despite the apparent influence of unsymmetric pith and knots, neither pith index nor knot size appeared to have a significant correlation to compressive strength. The average UCS from green tests adjusted to 12% moisture content using the ASTM dry/green ratio was predicted to be 33 MPa (4.8×10^3 lb/in^2). Results of dry tests showed an average UCS of 31 MPa (4.5×10^3 lb/in^2). Because these samples were dried below 12% moisture content, their UCS values should have averaged higher than that predicted using the “green” test results and the ASTM dry/green ratio. Results of a *t*-test to compare adjusted values for these two samples suggest that the mean values were significantly different at the 0.05 level of significance. The difference may have been due to the proportion of juvenile wood or to the fact that drying checks masked the reduction in cross section, giving a high estimate of cross sectional area.

Given that the ASTM D2555 dry/green ratio gave an unconservative estimate of member strength at 12% moisture content, an adjustment factor was derived from the data. A least squares linear regression analysis of compressive strength as a function of moisture content (Fig. 7) indicated that the dry/green ratio is 1.78 rather than 1.91. Using this adjustment resulted in an average UCS at 12% moisture content of 29.6 MPa (4.3×10^3 lb/in^2) with a 12% COV.

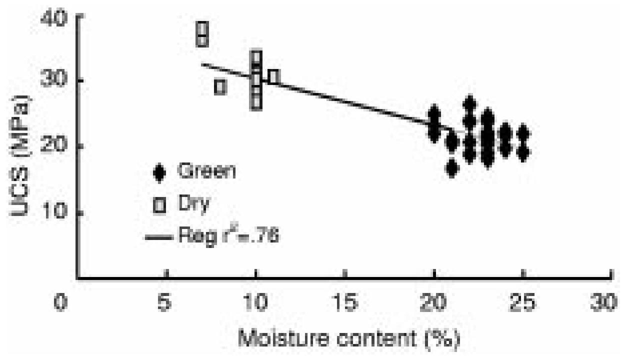

Figure 7—Relationship between UCS and moisture content for two samples suggests a dry/green ratio of 1.78.

The MOE (E_c) for the green samples averaged 3.86 GPa (560×10^3 lb/in^2) with a 23% COV. Adjusting these values to 12% moisture content using the ASTM dry/green ratio (1.27) gave an estimated dry MOE of 4.48 GPa (650×10^3 lb/in^2). The dry tests showed an average E_c of 5.16 GPa (750×10^3 lb/in^2) with a 20% COV. Assuming the ASTM dry/green ratio could be extended beyond the 12% to 30% range, we adjusted these values upward to 12% moisture content. This gave an average value of 4.97 GPa (720×10^3 lb/in^2) and 18% COV. Although the 4.48-GPa and 4.97-GPa values (650 and 720×10^3 lb/in^2, respectively) were not significantly different at the 0.05 level of significance, we nevertheless used a least squares regression of E_c against moisture content to check the ASTM ratio. The regression suggested that the dry/green ratio should be 1.62. Combining the samples using this ratio gave an average *E*c of 5 GPa (730×10^3 lb/in^2) with a 22% COV and 12% moisture content.

Figure 8 compares UCS and E_c for the two samples adjusted to 12% moisture content. In this case, the adjustments were 1.78 for UCS and 1.62 for MOE going from 30% to 12% moisture content. The ASTM D2899 standard procedure for the derivation of compression-parallel-to-grain design stress gives a value of 18 MPa (2.6×10^3 lb/in^2) at 12% moisture content. Removing the adjustment for duration of load (1.52) gives a value of 27.5 MPa (4×10^3 lb/in^2). This is close to the estimate made using the derived dry/green ratios. The ASTM D2899 compression-parallel-to-grain design value gives a short column design capacity of 231 kN (5.2×10^3 lbf) for a 127-mm- (5-in.-) diameter round Douglas-fir timber at 12% moisture content.

The longitudinal MOE is normally assumed to be the same for bending, tension, and compression. Thus, the E_c values measured for the full-size compression tests should provide an estimate of the *E* required for column stability calculations following the NDS procedures. However, measured values were lower than expected. Using the ASTM D2555 dry/green adjustment for Douglas-fir MOE to derive an average value

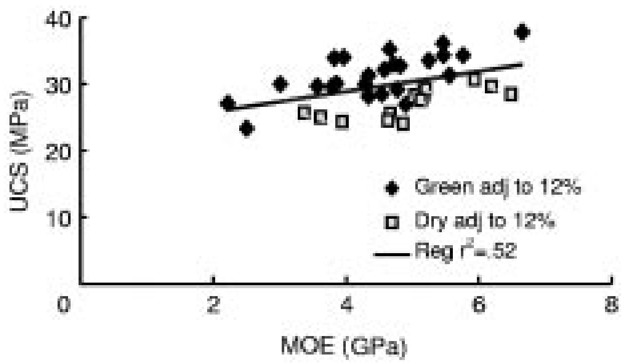

Figure 8—UCS adjusted to 12% moisture content using a dry/green (12%/30% moisture content) ratio of 1.78 for UCS and 1.62 for E_c.

of 4.4 GPa (650×10^3 lb/in^2) limits the design load to 39 kN (8.8×10^3 lbf) at 12% moisture content for a 2.43-m (8-ft) column. The additional 14 dry tests support increasing this average value to 5.03 GPa (730×10^3 lb/in^2), which would increase the design load to 41.4 kN (9.3×10^3 lbf).

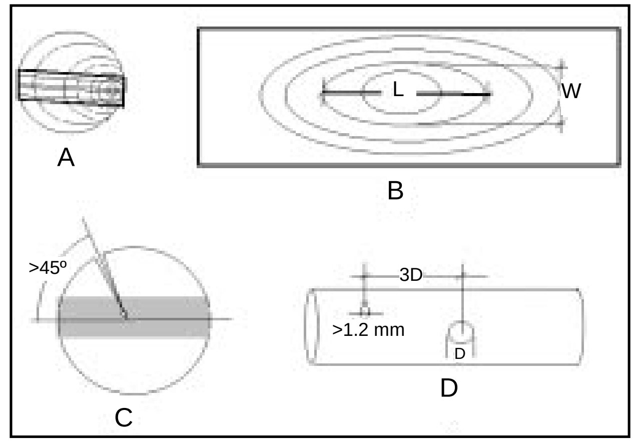

Figure 9—Joint detail: timber characteristics. Dowel nut should pass through the pith (A). If the surface annual ring pattern has a L/W ratio (B) less than 3, the timber should be rejected for structural applications. The dowel nut should be oriented at least 45° from any severe drying checks (C). Any knots greater than 1.2 mm (0.05 in.) in diameter should be at least 3 times the dowel diameter from the dowel hole (D).

Conclusions

A 44.5-mm- (1.75-in.-) diameter dowel-nut connector appears to be economically feasible at a design capacity of 44.5 kN (1.0×10^4 lbf) for a 127-mm- (5-in.-) diameter Douglas-fir peeler core. To achieve a reliable connection, however, the fabricator should be aware of variables that affect joint strength and failure mode. We conclude the following:

- This design stress is based on the assumption that the dowel nut is centered seven diameters (311 mm (12.25 in.)) from the end of the peeler core. The derivation considers bearing capacity, tension, and/or shear parallel to grain (ASTM D2899) and tension perpendicular to grain.
- The hole for the dowel-nut connector should be drilled after drying the peeler core to prevent problems caused by shrinkage of the hole and to assure that any drying checks are not aligned with the primary shear plane of the joint.
- Reaction wood should be aligned in the plane of the dowel as opposed to being in the areas stressed in tension on either side of the dowel.
- Angled grain should be avoided in the region of the connection. Such grain can be detected by a pattern of concentric ellipses formed by annual rings on a tangential surface of the peeler core. A pattern with a major/minor axis ratio of 3 or less should be avoided (Fig. 9).
- In this study, the 5th percentile axial compressive strength of full-sized sections was close to the value predicted following ASTM D2899 design procedures. Adjusted to 12% moisture content, the 127-mm- (5-in.-) diameter peeler core sections had a short column design capacity of 186 kN (4.2×10^4 lbf) and a 2.4-m (8-ft) column capacity of 41.4 kN (0.93×10^4 lbf).

Recommendations for Future Study

1. Tests should be conducted to assess the value of machining prior to drying as a means of minimizing the effects of drying checks. A saw kerf cut prior to drying may help control where splitting occurs. Holes drilled parallel to the log axis along the centroid may reduce splitting by opening an inner surface to evaporation.
2. Modification of joint parameters should be evaluated for a possible increase in joint efficiency. Reductions in dowel diameter, combined with the same or increased end distance, will increase the effective areas for tension parallel and perpendicular to grain as well as shear parallel to grain. By increasing resistance to tension and shear, the failure mode may be changed to a more ductile bearing deformation with little change in the average capacity of the connection.

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Appendix A—Pilot Tests of Dowel-Nut Connector

Eight joints were tested to assess their sensitivity to variations in joint configuration. Variables in these tests included dowel-nut diameter, type and location of the confinement device, specimen moisture content, and specimen length.

Four test peeler cores were used. The cores were initially 1.8 m (6 ft) long. After the first series of tests was completed, a 0.3-m (1-ft) length was cut from each end of the core, so that cores for the second series were 1.2 m (4 ft) long.

In all cases, the steel dowel nut was centered 0.25 m (10 in.) from the end of the specimen. For the first two tests, the steel dowel was 31.8 mm (1.25 in.) in diameter. When we observed ductile compression parallel-to-grain failures, we tried increasing the size of the dowel to 44.5 mm (1.75 in.) to determine whether joint load capacity could be increased without changing the mode of failure to tension parallel to grain.

The results of the pilot tests are summarized in Table 1.

The joint test sequence was as follows:

1. The first joint test (1A) included a 31.8-mm (1.25-in.) dowel-nut connector, a shipping band confinement strap fastened with a metal crimp, and a peeler core with a relatively high moisture content (probably 25%–30% at time of test). Because of the loose fit, the joint exhibited an initial failure at a relatively low load (62.3 kN (14×10^3 lbf)). Then, the confinement strap caused the load to climb to 70.3 kN (15.8×10^3 lbf). A second failure caused the load to drop to 48.9 kN (11×10^3 lbf). We then reinforced the failed end with a spiral bolt helix clamp and reloaded to 62.3 kN (14×10^3 lbf) before the final failure. The failure mode in this case was a combination of tension perpendicular to grain, which caused an initial crack, and reduction in size of the effective shear plane, followed by shear failure.
2. The second test (1B) was similar to the first except that a spiral bolt helix clamp was used on both ends of the specimen. In this case, the maximum load rose to 89 kN (20×10^3 lbf), and the failure mode was a combination of compression parallel to grain and tension perpendicular to grain. Both ends of the specimen appeared to exhibit approximately the same level of compression. We thought that improving confinement by increasing the dowel bearing area would increase joint capacity.
3. For the third test (8B), the diameter of the dowel nut was increased to 44.5 mm (1.75 in.) and a steel strap pipe clamp with a "T-bar" bolt type adjustment was tested. The pipe clamp was placed just above the dowel-nut hole. Because of the taper in the peeler core, we were not able to put the same clamp on the larger end, so we used the spiral bolt helix clamp. Both ends of the specimen were compressed equally. At a load of 93 kN (20.9×10^3 lbf), the smaller end split in tension perpendicular to grain at the part beyond the clamp. We reclamped this end and reloaded to 97.14 kN (21.84×10^3 lbf). This was a ductile failure in which the load dropped to 66.7 kN (15×10^3 lbf).
4. For the fourth test (10B), we placed two strap clamps on each end of the specimen. In this case, the failure was confined to compression parallel to grain, reaching a maximum load of 110.7 kN (24.9×10^3 lbf) and holding that load. We stopped the test at a total deformation in excess of 25 mm (1 in.). The remaining tests were conducted on the same peeler cores as those used for the previous tests except that the failed material was removed from the specimen (0.3 m (1 ft) from each end) and the ends were re-machined.
5. Results of joint test 1A2 were significantly different than those of test 1A1. In this case, the maximum load of 150.3 kN (33.8×10^3 lbf) resulted in a combined shear and tension parallel-to-grain failure. Each specimen end had only one pipe clamp. The upper end, away from the active load head, was reinforced with an embedded metal plate connector (MPC) (truss plate) to aid in resisting tension perpendicular to grain. In the case of test 1A2, the pipe clamps were located 25 mm (1 in.) away from the dowel-nut hole, toward the end of the peeler core. Unlike the joints in test 8B, joint 1A2 exhibited no tendency to split as a result of tension perpendicular to grain. Rather, the failure was a combination of shear and tension parallel to grain on the specimen end without the MPC. The material was quite a bit drier the second time around, and drying checks that opened up played a role in the failure.
6. Results of the 1B2 test were similar to those of 1A2 except that a second clamp was added to the end without the MPC reinforcement. Maximum load was 143.2 kN

Table 1—Results of pilot tests of dowel-nut connector

		Moisture content (%)		Specific gravity		
ID	Length (m (ft))	End A	End B	End A	End B	Max load (kN ($\times 10^3$ lbf))
1A1	1.8 (6)	—	—	0.43	0.47	70.3 (15.8)
1A2	1.2 (4)	9	11	—	—	150.3 (33.8)
1B1	1.8 (6)	—	—	0.41	0.39	89.0 (20.0)
1B2	1.2 (4)	9	11	—	—	143.2 (32.2)
8B1	1.8 (6)	—	—	0.40	0.41	97.1 (21.8)
8B2	1.2 (4)	20	18	—	—	118.7 (26.7)
10B1	1.8 (6)	—	—	0.45	0.47	110.7 (24.9)
10B2	1.2 (4)	18	19	—	—	138.0 (31.0)

(32.2 × 10^3 lbf). The failure was the same as that observed for test 1A1—combined shear and tension parallel to grain at the dowel-nut hole. This failure occurred on the specimen end with the two pipe clamps.

7. The retest of peeler core 8B was also similar to that of peeler core 1A except that the MPC end was placed on the bottom, toward the active load head. In this case the MPC end failed at a load of 118.7kN (26.7 × 10^3 lbf).

8. For the 10B retest, strap clamps were located 25 mm (1 in.) outside the dowel connector holes, MPC was on the active load-head end, and the clamp was on the opposite end. Failure at 138 kN (31 × 10^3 lbf) occurred on the upper end of the specimen. The mechanism of failure was shear and tension parallel to grain.

The shear and tension-parallel-to-grain failure mode is less desirable than the compression-parallel-to-grain mode because it is more brash, causing a sudden drop in joint capacity. This seems to be influenced primarily by the change in moisture content. As the compression parallel-to-grain strength of wood almost doubles from green to dry, it is possible that increasing the dowel-nut diameter caused the failure mode to shift to tension parallel to grain in the dry material.

Appendix B—Test Results

Tables 2 and 3 give the results of tension tests of the dowel-nut connection in 127-mm- (5-in.-) diameter Douglas-fir peeler cores and compression tests of full-size sections, respectively. The joint tests (Table 2) are described in the main body of this report. Tables 3 and 4 compare tests conducted in green and dry conditions, respectively. The "slope" value listed in these tables refers to the slope of the load–displacement curve determined by linear regression over the displacement range of 20% to 40% of the maximum load. The elastic limit value was determined as the point where the linear regression deviated from the measured load by more than 1%. In most cases, the load–displacement curves for the two end-joints were almost parallel, to the point where one began to fail. Figure 10 shows the extreme example where the slopes ranged from 96 to 189 kN/mm (550 to 1,080 × 10^3 lbf/in). Note that beyond 5 kN/mm (29 × 10^3 lbf/in), both joints exhibited accelerating deformation.

Compressive load–displacement slopes and maximum loads are shown in Tables 3 and 4. Results reported in Table 3 are from samples tested at varying moisture content levels, all greater than 20%. Results reported in Table 4 are from samples tested at moisture content under 12%. All results were adjusted to 12% moisture content using linear interpolation dry/green ratio derived for moisture content changes from 30% to 12% (1.78 for ultimate compressive stress and –1.25 for modulus of elasticity (ASTM D2555)).

Table 2—Results of dowel-nut connection tests in Douglas-fir peeler cores

ID	Growth rate[a] (r/cm (rpi))	Pith index	SG	MC (%)	Maximum load (kN (×10^3 lbf))	Slope (kN/mm (×10^3 lbf/in))	Elastic limit (kN (×10^3 lbf))	Comment[b]
J-5-1	2 (2.0)	0.50	0.44	10	101 (22.6)	158.5 (905)	89 (20)	Joint knot affects parallel tension
J-5-2	3 (7.5)	0.14	0.41	10	159 (35.7)	159.7 (912)	142 (32)	Shear and tension perp to grain
J-5-3	5 (12.3)	0.57	0.45	10	165 (37.1)	155.3 (887)	151 (34)	Shear and tension perp to grain
J-5-4	2 (5.2)	0.60	0.37	8	126 (28.2)	120.5 (688)	111 (25)	Shear
J-5-5	3 (7.0)	0.14	0.41	10	106 (23.9)	173.3 (990)	89 (20)	Tension perp to grain
J-5-6	3 (7.5)	0.67	0.43	11	123 (27.6)	146.7 (838)	120 (27)	Shear and tension perp to grain
J-5-7	3 (7.3)	0.54	0.40	10	117 (26.4)	134.3 (767)	116 (26)	Tension parallel to grain +shear
J-5-8	4 (11.3)	0.55	0.49	12	164 (36.9)	186.7 (1,066)	133 (30)	Shear
J-5-9	2 (6.3)	0.29	0.45	10	131 (29.5)	204.8 (1,170)	129 (29)	Shear
J-5-10	4 (10.0)	0.20	0.45	10	108 (24.4)	130.6 (746)	107 (24)	Tension parallel to grain
J-5-11	2 (4.5)	0.09	0.44	7	102 (23.0)	187.9 (1,073)	102 (23)	Tension parallel to grain + shear
J-5-12	4 (9.0)	0	0.49	11	161 (36.2)	131.0 (550)	129 (29)	Tension parallel to grain
J-5-13	3 (8.0)	0.28	0.4	10	139 (31.3)	113.6 (649)	125 (28)	Tension parallel to grain + shear
J-5-14	2 (5.3)	0.31	0.43	10	102 (23.0)	164.2 (938)	102 (23)	Shear + tension perp to grain
J-5-15	2 (5.7)	0.21	0.43	10	137 (30.8)	150.2 (858)	120 (27)	Brash tensile failure parallel to grain; splintery latewood
J-5-16	3 (8)	0.85	0.43	10	127 (28.6)	114.9 (656)	120 (27)	Compression parallel to grain; ductile tension perp to grain
Average			0.4	7.7	131 (29.1)	151.6 (856)	120 (26.5)	
COV			7%	53%	16% 17%	15% 18%	8% 14%	
5th percentile			0.4	0.8	95 (20.5)	114.0 (596)	103 (20.3)	

[a]rpi designates rings per inch; r/cm, rings per centimer.
[b]Parallel designates parallel to grain; perp, perpendicular to grain.

Table 3a—Summary of compression parallel-to-grain test results for green Douglas-fir peeler cores[a]—SI units

ID	Growth rate (r/cm)	Pith index	SG	MC (%)	*A* (cm^2)	Slope (kN/mm)	P_{max} (kN)	UCS (MPa)	MOE (GPa)	UCS @ 12% MC (MPa)	MOE @ 12% MC (GPa)
C-5-1	3	0.45	0.44	25	3.04	120.8	278	22	4.8	37	5.7
C-5-2	3	0.22	0.39	24	3.43	112.3	309	22	4.0	35	4.7
C-5-3	2	0.39	0.39	23	3.22	102.8	292	22	3.9	34	4.5
C-5-4	2	0.50	0.42	23	2.98	91.9	262	21	3.7	33	4.3
C-5-5	2	0.20	0.41	23	3.16	121.9	322	24	4.7	38	5.4
C-5-6	3	0.50	0.45	22	3.30	92.8	326	24	3.4	36	3.9
C-5-7	3	0.90	0.42	21	3.08	56.6	216	17	2.2	25	2.5
C-5-8	3	0.95	0.38	22	3.22	81.8	278	21	3.1	31	3.5
C-5-9	4	0.40	0.40	23	3.29	100.5	261	19	3.7	30	4.3
C-5-10	3	0.25	0.45	25	3.36	99.8	269	19	3.6	32	4.2
C-5-11	3	0.27	0.35	23	3.15	107.7	239	18	4.2	28	4.8
C-5-12	4	0.40	0.46	22	2.90	45.5	228	19	1.9	29	2.2
C-5-13	4	0.23	0.38	23	3.16	85.8	268	20	3.3	32	3.8
C-5-14	3	0.31	0.43	22	3.19	124.9	318	24	4.8	36	5.4
C-5-15	6	0.41	0.42	20	3.43	94.2	314	22	3.4	31	3.7
C-5-16	2	0.33	0.39	21	3.30	108.4	282	20	4.0	30	4.5
C-5-17	3	0.56	0.42	24	3.29	87.6	305	22	3.2	36	3.8
C-5-18	3	0.21	0.37	23	3.16	107.9	292	22	4.1	35	4.8
C-5-19	3	0.31	0.46	24	3.04	62.9	250	20	2.6	32	3.0
C-5-20	4	0.86	0.50	23	3.30	108.9	328	24	4.0	37	4.6
C-5-21	2	0.20	0.45	22	3.12	123.1	342	26	5.8	40	6.6
C-5-22	2	0.20	0.37	20	3.07	98.8	318	25	4.7	35	5.2
C-5-23	4	0.80	0.41	20	3.02	102.1	293	23	5.0	33	5.5
C-5-24	3	0.25	0.39	21	3.10	89.1	271	21	4.2	31	4.7
Average			0.42	23	3.18	97.0	286	22	3.9	33	4.4
COV			9%	6%	4%	21%	12%	11%	23%	11%	23%
5th percentile			0.40	20	2.9	62.0	229	17.6	2.3	27	2.7

[a]P_{max}, maximum load; UCS, ultimate compressive stress; MOE, modulus of elasticity.

Table 3b—Summary of compression parallel-to-grain test results for green Douglas-fir peeler cores[a]—inch–pound units

ID	Growth rate (rpi)	Pith index	SG	MC (%)	*A* (in^2)	Slope ($\times 10^3$ lbf/in)	P_{max} ($\times 10^3$ lbf)	UCS ($\times 10^3$ lb/in^2)	MOE ($\times 10^3$ lb/in^2)	UCS @ 12% MC ($\times 10^3$ lb/in^2)	MOE @ 12% MC ($\times 10^3$ lb/in^2)
C-5-1	8	0.45	0.44	25	19.6	690	62.4	3.18	700	5.24	835
C-5-2	8	0.22	0.39	24	22.1	641	69.5	3.15	580	5.04	683
C-5-3	5	0.39	0.39	23	20.8	587	65.7	3.17	570	4.93	664
C-5-4	6	0.50	0.42	23	19.2	525	59.0	3.07	540	4.78	629
C-5-5	4	0.20	0.41	23	20.4	696	72.4	3.54	680	5.51	792
C-5-6	7	0.50	0.45	22	21.3	530	73.3	3.45	500	5.19	575
C-5-7	8	0.90	0.42	21	19.9	323	48.5	2.43	320	3.54	363
C-5-8	7	0.95	0.38	22	20.8	467	62.5	3.01	450	4.53	518
C-5-9	9	0.40	0.40	24	21.2	574	58.6	2.76	540	4.36	633
C-5-10	8	0.25	0.45	24	21.7	570	60.4	2.78	520	4.54	618
C-5-11	7	0.27	0.35	22	20.3	615	53.7	2.65	610	4.06	706
C-5-12	9	0.40	0.46	22	18.7	260	51.2	2.74	280	4.13	322
C-5-13	9	0.23	0.38	23	20.4	490	60.3	2.95	480	4.60	560
C-5-14	8	0.31	0.43	22	20.6	713	71.6	3.48	690	5.26	795
C-5-15	14	0.41	0.42	20	22.1	538	70.5	3.20	490	4.45	547
C-5-16	5	0.33	0.39	21	21.3	619	63.3	2.97	580	4.37	661
C-5-17	8	0.58	0.42	24	21.2	500	68.6	3.23	470	5.16	553
C-5-18	7	0.21	0.37	23	20.4	616	65.6	3.21	600	5.00	700
C-5-19	8	0.31	0.46	24	19.6	359	56.1	2.87	370	4.55	434
C-5-20	11	0.86	0.50	23	21.3	622	73.7	3.46	580	5.45	679
C-5-21	5	0.86	0.45	22	20.1	703	76.9	3.82	840	5.66	960
C-5-22	5	0.20	0.37	20	19.8	564	71.5	3.62	680	5.13	765
C-5-23	9	0.80	0.41	20	19.5	583	65.8	3.38	720	4.79	808
C-5-24	8	0.25	0.39	21	20.0	509	60.9	3.04	610	4.47	695
Average			0.41	22	20.5	554	64	3.13	558	4.78	646
COV			9%	6%	4%	21%	12%	11%	23%	11%	23%
5th percentile			0.35	20	18.99	355.31	51.3	2.56	336	3.90	391

[a]P_{max}, maximum load; UCS, ultimate compressive stress; MOE, modulus of elasticity.

Table 4a—Dry compression parallel-to-grain tests of samples cut from joint test specimens[a]—SI units

ID	Growth rate (r/cm)	Pith index	SG	MC (%)	cx[b] (cm^2)	Slope (kN/mm)	P_{max} (kN)	UCS (MPa)	MOE (GPa)	UCS[c] (MPa)	MOE[c] (GPa)
J-5-3	5	0.57	0.45	10	132.81	135.8	412	31	5.2	30	5.0
J-5-4	2	0.60	0.37	8	132.29	134.6	385	29	5.2	26	4.9
J-5-5	3	0.14	0.41	10	116.23	85.3	319	27	3.7	26	3.6
J-5-6	5	0.57	0.45	10	127.65	134.1	410	32	5.3	31	5.2
J-5-7	3	0.54	0.40	10	123.65	98.9	331	27	4.1	26	4.0
J-5-8	3	0.14	0.41	10	140.16	147.3	437	31	5.3	30	5.2
J-5-9	3	0.67	0.43	0	132.29	159.3	445	34	6.1	32	6.0
J-5-10	3	0.54	0.40	0	126.16	119.5	354	28	4.8	27	4.7
J-5-11	4	0.55	0.49	0	125.13	172.7	455	36	7.0	32	6.5
J-5-12	2	0.29	0.45	10	126.16	86.2	355	28	3.5	27	3.4
J-5-13	4	0.20	0.45	10	130.23	122.4	351	27	4.8	26	4.6
J-5-14	2	0.09	0.44	7	130.23	171.6	495	38	6.7	34	6.2
J-5-15	4	0	0.49	11	126.61	131.5	388	31	5.3	30	5.2
J-5-16	3	0.28	0.40	10	129.71	135.0	393	30	5.3	29	5.1
Average			0.40	7.3	127.80	130.3	394.5	31	5	29	5.0
COV			8%	58%	4%	21%	13%	11%	20%	9%	18%
5th percentile			0.37	–0.14	118.13	81.6	304.47	24.73	3.4	24.30	3.4

[a]Load assumed to be uniformly distributed to cross section. Strain gauge length in all cases was 508 mm (20 in.).
[b]Cross section.
[c]Data for UCS and MOE were adjusted to 12% MC.

Table 4b—Dry compression parallel to grain tests of samples cut from joint test specimens[a]—inch–pound units

ID	Growth rate (rpi)	Pith index	SG	MC (%)	cx[b] (in^2)	Slope ($\times 10^3$ lbf/in)	P_{max} ($\times 10^3$ lbf)	UCS ($\times 10^3$ lb/in^2)	MOE ($\times 10^3$ lb/in^2)	UCS[c] ($\times 10^3$ lb/in^2)	MOE[c] ($\times 10^3$ lb/in^2)
J-5-3	12	0.57	0.45	10	20.59	776	92.7	4.50	750	4.30	732
J-5-4	5	0.6	0.37	8	20.51	769	86.6	4.22	750	3.84	708
J-5-5	8	0.14	0.41	10	18.02	487	71.8	3.98	540	3.80	526
J-5-6	12	0.57	0.45	10	19.79	766	92.1	4.65	770	4.44	752
J-5-7	7	0.54	0.4	10	19.17	565	74.3	3.88	590	3.70	573
J-5-8	7	0.14	0.41	10	21.73	841	98.2	4.52	770	4.31	753
J-5-9	8	0.67	0.43	10	20.51	910	100.2	4.88	890	4.66	863
J-5-10	7	0.54	0.40	10	19.56	682	79.7	4.07	700	3.89	678
J-5-11	11	0.55	0.49	7	19.4	986	102.4	5.28	1,020	4.68	946
J-5-12	6	0.29	0.45	10	19.56	492	79.8	4.08	500	3.90	489
J-5-13	10	0.2	0.45	10	20.19	699	78.9	3.91	690	3.73	673
J-5-14	4	0.09	0.44	7	20.19	980	111.2	5.51	970	4.31	904
J-5-15	9	0	0.49	11	19.63	751	87.3	4.45	760	4.35	755
J-5-16	8	0.28	0.40	10	20.11	771	88.4	4.40	770	4.20	745
Average			0.40	9.6	19.80	744	88.7	4.47	748	4.21	721
COV			8%	13%	4%	21%	13%	11%	20%	9%	18%
5th percentile			0.40	7.41	18.32	465.9	68.4	3.59	—	3.52	487.80

[a]Load assumed to be uniformly distributed to cross section. Strain gauge length in all cases was 508 mm (20 in.).
[b]Cross section.
[c]Data for UCS and MOE were adjusted to 12% MC.

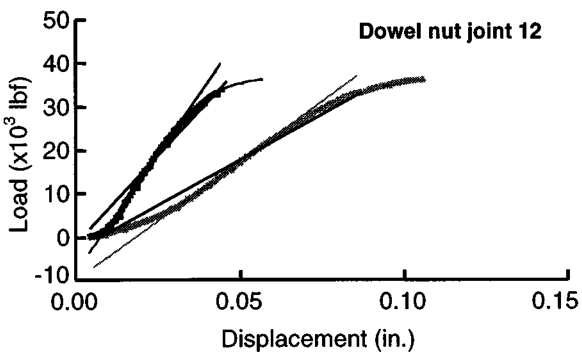

Figure 10—Load–displacement curves for end joints.

Appendix C—Design of Dowel-Nut Connectors

This appendix provides a derivation of estimates of the average strength of dowel-nut connectors in Douglas-fir peeler cores and a recommended nominal design value based on published strength values (ASTM D2555 (ASTM 1998)) and conventional design derivation procedures (AF&PA National Design Specification (ANSI/AF&PA 1997) and ASTM D245 and ASTM D1761 (ASTM 1993b and ASTM 1995, respectively).

Assumed joint parameters

Nominal diameter of dowel nut	$D_d = 1.75$ in.
Nominal diameter of peeler core	$D_c = 5$ in.
Bearing length in timber (core diam–threaded rod hole diam)	$1 = D_c - 1$ in.
Bearing area, projected	$A_b = D_d D_c$
Tensile area	$A_t = \pi(0.5\, D_c)^2 - A_b$
Dowel center–end distance	$ND_c = 10$ in.
Shear area	$A_{shr} = (ND_c - 0.5\, D_c)D_c$

Bearing parallel-to-grain failure

Following the NDS guideline for dowel (bolted) connections loaded parallel to grain at a reduced end distance (<7D), the expected average strength of the connection would be as follows:

Dowel bearing strength (NDS Table 8A)		$F_{es} = 5{,}500$ lb/in^2
Expected ultimate bearing strength of test joint		$F_{es}\, D_d 1 \dfrac{ND_c}{7D_d} = 3.143 \times 10^4$ lb/in^2
Nominal design value (NDS)	$Z = D_d 1(F_{es}/4)$	$Z = 9.625 \times 10^3$ lb/in^2
Design for wind	$Z_w = Z\ 1.15$ lb	$Z_w = 1/107 \times 10^4$ lb/in^2

Tension parallel-to-grain failure

NDS design stress for Douglas-fir North Construction grade 4 by 4	$F_t = 950$ lb/in^2
Design load capacity for 10-year dry use	$F_t A_t = 1.034 \times 10^4$ lb/in^2
Expected average ultimate strength	
ASTM D245, assuming COV of 20%	$\dfrac{F_t\, 2.1 A_t}{1 - 1.645(0.2)} = 3.23 \times 10^4$ lb/in^2

Shear parallel-to-grain failure

This type of failure appears as a block pushed between two shear planes.

Shear area—two shear planes	$A_v = 2A_{shr}$
NDS design shear stress for Douglas-fir North Construction grade 4 by 4	$F_v = 95$ lb/in^2
Design load capacity based on sawn timber	$F_v A_v = 7.125 \times 10^3$ lb/in^2
Green timber design value based on ASTM D2899	$F_{vg} = 947 \cdot \dfrac{(1 - 1.645[0.13])}{5.47}$
(The factor 1/5.47 consists of a 0.75 adjustment for SR and 1/4.1 for DOL and FS)	$F_{vg} = 136.103$ lb/in^2
Shear strength, average at 12% MC (ASTM D2555)	$F_{vd} = F_{vg} 1.48$
	$F_d = 201.433$ lb/in^2
Load capacity	$F_{vd} A_v = 1.511 \times 10^4$ lb/in^2