Space-frame connection for small-diameter round timber

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ABSTRACT

To promote more efficient use of small-diameter timber, research efforts are being focused on the development and evaluation of connection methods that can be easily applied to non-standard round wood profiles. This report summarizes an evaluation of a "dowel-nut connection" as an option for the use of Douglas-fir peeler cores in three-dimensional truss or "space-frame" structural applications. Joint details were selected on the basis of ease of fabrication, joint strength, failure mode, and cost. It was concluded that the cores should be dried close to expected ambient conditions prior to machining. Test results support a design load of 45 kN in a 12.7-cm-diameter peeler core, and recommended joint details are intended to provide a ductile compression parallel to grain failure mode in the event of accidental overload.

INTRODUCTION

The USDA Forest Service faces the task of managing a growing problem of overstocking of small-diameter timber in National Forests. This overstocking creates a potential for loss due to fire or disease. Thick stands of small-diameter trees are more vulnerable than well-spaced stands of larger trees. It is difficult to encourage timber users to bid on timber sales involving selective cutting of only the small-diameter material without a market for turning harvesting costs into a profit. An option for increasing the value of small-diameter timber is to expand round timber structural markets.

As with most wood structural applications, connections will play a key role in expanding the use of round wood. Developing the strength and stiffness capacity of round timbers through a mechanical connection is more of a challenge than for dimension lumber. Due to the smaller surface-to-volume ratio, it is difficult to develop large capacities using connections that rely on a distribution of forces over the unmachined surface. Machining the timbers to accommodate mechanical connections can significantly reduce load capacity at the connection and also adds to the cost of using these timbers. Research to develop a feasible connector must pay attention to ease of fabrication and cost of materials.

The dowel-nut connection is one connection detail that may be relatively easy to fabricate and economically feasible for use with round-wood peeler cores. This connection, commonly used in "knock-down" furniture, is relatively easy to fabricate using inexpensive materials and is compatible with trussed applications. However, there are no test data available to support design assumptions.

OBJECTIVES

The primary objective of this study was to evaluate the efficacy of using dowel-nut connections as a means of promoting value-added structural applications of small-diameter round timber. Tests were conducted to provide a basis for verifying prediction models and to promote joint configurations that exhibit ductile failure modes.

A secondary objective was to provide an economical joint configuration. A cooperator in this study was looking to make use of Douglas-fir peeler cores as structural elements in the space-frame structural assembly. As a waste product of the plywood industry, peeler cores offer a relatively low-cost resource; however, their efficacy is dependent on efficiency of the connections.

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METHODS

Tests conducted to characterize the strength of dowel-nut connections in Douglas-fir peeler cores for space frame applications focused primarily on axial tension capacity. Proposed models to predict the strength of these connections consider four failure modes: tension and compression parallel to grain, longitudinal shear, and tension perpendicular to the grain. The goal in this case was to adopt a joint configuration with a bias toward a ductile compression-parallel-to-the-grain failure mode.

Material
The round timbers used in this study were Douglas-fir peeler cores, a by-product of the plywood industry. We used two sizes, 12.7 cm (5 in) in diameter and 16.5 cm (6½ in) in diameter. The average growth rate of the smaller cores was roughly half that of the larger ones, but specific gravity (SG =0.44) was not affected by growth rate. These cores were not pith centered, and they had moisture contents in the range of 25% to 30% at the time they were delivered.

The fact that this SG value is lower than the published value for Douglas-fir is likely due to the high portion of juvenile wood. Juvenile wood normally predominates in the first 10 to 20 years of growth and exhibits lower density and lower strength and stiffness than wood further from the pith. The pith index (the distance from the cross-section centroid to the pith divided by the cross-section radius) values ranged from 0 to 0.9, meaning that in some cases the juvenile wood portion was not fully surrounded by mature wood. The larger cores had lower pith indices (pith more centrally located) and less wood removed, so their net juvenile portion was not much different than that of the smaller cores.

In addition to the presence of juvenile wood, these cores also exhibited reaction wood and angled grain, which could have a significant effect on material strength.

Joint configuration
The test connections (Figure 1) were fabricated from relatively high-yield 0.39- to 0.41-GPa steel. Each joint consisted of a "dowel-nut" cut from solid round hot roll steel (31.7 to 44.4 mm diameter) and a 19-mm-diameter threaded rod. The solid round "dowel" was cut 127 mm long and had a threaded hole aligned with its diameter at mid-length. The threaded rod hole, however, was drilled 6.35 mm oversize and may have had a beneficial effect on drying. Pilot tests were conducted using a 31.7-mm-diameter steel dowel. However, the primary tests joints discussed in this paper were fabricated using a 44.45-mm-diameter steel dowel.

Several types of restraining devices were tried to prevent splitting of the timber due to tension perpendicular to the grain and shear between the dowel nut and the end of the core. The device selected on the basis of ease of application, restraining capability, and cost was a metal strap pipe clamp with a threaded "T-bar" detail for adjusting the restraining force (Figure 1). It had a stainless steel strap 12.7 mm wide and 0.762 mm thick. The clamp was tightened with a torque of approximately 69 Nm. Tests of the 16.5-cm cores included the addition of steel pins 1.11 cm in diameter oriented perpendicular to and 1 inch above the dowel nut to help restrain tension and shear type failures. For these tests, one end of the core had the two pins with a metal plate connector embedded in the end grain and the other end had two strap clamps (Figure 2).

Joint test procedures
The dowel-nut connections were loaded in tension to provide load-deformation plots for two connections at a time. A dowel-nut joint on each end of the peeler core provided threaded rods that were used to attach the test core to the machine heads. Load was applied maintaining a constant displacement rate of 0.254 mm per minute to attain maximum strain in 5 to 10 minutes. As load was applied in axial tension, the displacements of the threaded rods were measured relative to the ends of the peeler core for both connections to the point of failure using linear variable differential transformers (LVDTs) with a 6.4-mm displacement range. The joints were loaded in series with a load cell for digital recording of the load-deformation curve. The test continued either until the load 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 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. Visual inspection was performed to determine the failure mode, any influence due to knots or other defects, pith index (location with respect to center divided by radius), and growth rate.

Compressive load and displacement were measured in both green and dry conditions as a means of characterizing strength and stiffness of the gross section of the peeler cores. All test results were adjusted to 12 % by interpolation of the ASTM

D2555 (ASTM 1996) dry/green (12%/30%) ratios (1.99 for stress and 1.27 for compressive modulus of elasticity E_c). Results were compared using a t-test for mean difference and the dry/green ratios were checked using least squares linear regression. These test results were compared with published values based on small clear tests of Douglas-fir.

RESULTS

Moisture content proved to be a critical variable. It not only affects the strength and stiffness of the joint but also physical properties of the machined surfaces and the peeler core, which in turn affect the reliability of the connection. Quality of the core in the area of the connection and the size and placement of the dowel nut also play a critical role in determining the capacity of these connections.

Moisture effects
Moisture content appeared to influence both strength and failure mode. The pilot tests conducted using green material resulted in ductile failures, while tests conducted using dry material exhibited brash failures. The failures in the first set of pilot tests were primarily in compression parallel to the grain as the dowel nut was pulled into the end grain. A second series of pilot tests conducted using re-fabricated connections in dryer specimens indicated a significant improvement in strength and stiffness; however, greater variability in failure mode was seen because drying increased the proportional limit stress in compression parallel to the grain, causing tension and shear stress parallel to the grain to exceed their dry threshold limits. Comparing test joints in the 16.5-cm cores with those in the 12.7-cm cores (Table 1), the failure mode change from brash to ductile may have been influenced by moisture—the larger cores had an average 14% moisture content compared with 10% for the smaller ones.

Machining wood prior to drying also causes problems associated with wood shrinkage. Drying checks form along the grain, reducing shear parallel to the dowel nut shear plane, thus reducing effective shear area. A second effect is that holes drilled through the cores shrank as the cores dried, making it difficult to insert the dowel nut if the hole was not oversized in the green condition and causing a split due to tension perpendicular to the grain when the dowel was installed in the green condition.

Material quality
For the series of joint tests conducted to assess design values for the dowel-nut connection fabricated and tested in the dry condition, we found that material quality played a major role in joint performance. Drying checks, a high pith index, reaction wood, and angled grain can critically affect joint load capacity. The fact that the test joint timbers contained any of these characteristics did not necessarily mean that they had low strength, but the combination of characteristics and location with respect to the joint played a major role in joint load capacity and failure mode.

Drying the joints increased stiffness and strength but also precipitated a change in failure modes by opening drying checks in the area of the dowel hole. Drying checks oriented at an angle less than 45° to the dowel hole reduced the effective shear area or tension-perpendicular-to-the-grain area, increasing the probability of an early failure. When a failure occurred in a plane parallel to but off center of the dowel, tensile force was distributed to the wood on one side of the dowel hole, leaving only 36.8 cm^2 of wood to carry the tensile force. When drying checks were oriented at an angle greater than 45° to the dowel hole, they were less likely to contribute to a weak plane for shear or tension-perpendicular-to-grain stress.

Drying also caused a significant increase in the compressive modulus of elasticity and yield stress. For the tests of dryer material, there was little if any apparent compression parallel to the grain for the 12.7-cm-diameter peeler cores with a 44.4-mm-diameter dowel. Failures in this case were due mostly to tension and shear parallel to the grain. In subsequent tests using the larger peeler cores (16.5 cm diameter), we eliminated tensile failures by using the same size dowel nut and leaving a greater cross-sectional area to carry tensile loads. In this case, the connections exhibited failures that were predominately compressive.

Joint configuration
As load was applied, the dowel nut compressed wood toward the end of the core. This outward force resulted in a tendency for wood above the confinement band to split due to tension-perpendicular-to-the-grain stress as two halves of the peeler core tended to rotate away from the plane of compressive stress. After seeing this trend in the pilot tests, a second confinement band was added near the end of the peeler core. Later, the second band was replaced with a truss plate pressed into the end of the timber.

Failure modes

The dry joint test results exhibited three predominant failure modes. All were influenced to some degree by the reduction in moisture content (Figure 3). The most common failure mode was the combined shear and tension-parallel-to-grain failure. The second most common failure mode was one in which there was no sign of tensile failure: shear in two planes, resulting in a section popping out of the end. In a couple instances, the failure initiated as tension perpendicular to the grain, appearing as a single split in a plane parallel and through the dowel hole. In many cases, it appeared that tension perpendicular to grain and shear acted together in splitting the timber from the dowel hole to the end. Only 1 of 16 joints in the 12.7-cm-diameter cores exhibited any sign of a bearing failure—a sharp contrast to results of pilot tests. On the other hand, failures in 3 of 5 of the 16.5-cm core tests were attributed to compression parallel to the grain. The other two exhibited shear parallel to the grain along planes running parallel and tangent to the dowel nut hole. Three of the failures occurred on the end with the two 1.11-cm-diameter threaded rods (Figure 3).

The confinement bands, which served to reinforce the specimens against tension-perpendicular-to-the-grain failures in the pilot tests, continued to serve in that capacity in the dryer test specimens. The lower incidence of bearing deformation and Poisson's effect pushing fibers apart made the bands seem less highly stressed in these dryer test samples. In one test, however, the steel band actually failed in tension, and in another the confinement stress, built up during the test, left compression-perpendicular-to-the-grain bearing deformations in the surface of the timber (Wolfe et al. 2000). In these cases, failures were predominately due to tension perpendicular to the grain, indicating need for greater reinforcement against tension perpendicular to grain.

Compression Tests

Failures in the compression tests appeared as compression wrinkles in the surface. These were most apparent around the knots. For the 12.7-cm-diameter sample with the lowest compressive modulus of elasticity E_c, the failure involved shear displacement initiating at a drying check in an area of juvenile wood close to one surface. In several cases of samples with high pith index, the swivel bearing plate of the active load head tilted to accommodate the lower E_c of the juvenile wood zone.

ANALYSIS OF RESULTS

Moisture Effects on Strength

The most apparent effect of moisture content was related to changes in wood strength and stiffness with drying. Compression test values increased from an average of 21.3 MPa at >20% moisture content (MC) to an average of 31 MPa when dried to 12% MC. The modulus of elasticity in compression changed from 3.86 GPa to 5.16 GPa going from green to dry (12% MC) condition. The test dry/green ratios (1.78 and 1.62 for strength and modulus of elasticity, respectively) were slightly different than those values published in the *Wood Handbook* (FPL 1999) (1.91 and 1.16, respectively).

Material Quality Effects

Material quality is also a major concern in the design of these dowel-nut connections. When the dowel hole is drilled through a section having a high pith index or steeply angled grain, its strength is likely to be compromised. When the pith is off center but in line with the dowel, it may cause eccentric loading on the dowel in that the compressive modulus of elasticity of the wood will be significantly lower over one half the bearing area than it is over the other half. This results in bending of the threaded rod as load is applied. If the pith or badly angled grain occurs in the area of the section carrying tensile forces, the tensile strength is reduced in those areas, thus reducing the joint capacity.

Both angled grain and pith index can be evaluated by visual inspection and handled by proper specification. If there are more than 20 rings between the pith and the outer surface, load eccentricity should not be a problem at design load levels. Steeply angled grain can be detected by inspecting grain patterns on the surface of the timber. When an elliptical pattern of contrasting earlywood/latewood appears on the surface, it is an indication that off-axis grain patterns are present. The ratio of the axes (length parallel to core axis against width perpendicular to core axis) should be limited to no less than 3 in the area of the dowel hole.

Joint Strength

The average strength resulting from 16 tests of the 12.7-cm cores was 130 kN; for 5 tests of the 16.5-cm cores, the average strength was 174 kN. Connections in the larger cores had 52% more bearing area, but the average strength advantage appears to be only 34%. Possible reasons for this difference include the sample sizes being compared, moisture effects, and basic material property differences.

Because the sample sizes are not equal, it is more appropriate to compare confidence limits. The fact that two joints were involved in each test means that we actually had a sample size of 32 for the smaller core tests and 12 for the larger ones. The smaller core joints had a coefficient of variation of 17%, whereas the larger cores had only a 6% variation. Using a Student's *t*-distribution to estimate the 90% confidence interval for these mean values, we get values ranging from 123 to 137 kN for the smaller cores and 168 to 179 kN for the larger cores, with ratios ranging from 1.31 to 1.37.

The dry/green compression strength ratio of 1.78 was determined for a moisture change from 12% to 30% MC. Assuming a linear relationship, this translates to a 17% strength difference between the small cores (10% MC) and the larger ones (14% MC).

As for material properties, the smaller cores had a slower growth rate, and the connections exhibited a range of failure modes. Despite the slower growth rate, the specific gravity values were essentially the same for both sizes. Due to the smaller tension-to-bearing-area ratio (Table 1) the smaller core connections exhibited a greater incidence of tension-parallel-to-grain failures occurring in conjunction with shear and tension perpendicular to the grain. This led to greater variability but perhaps a slightly higher strength than if the failure had been limited to compression. Joints in the larger cores exhibited no tensile failures.

Due to lower variability in the larger core connection tests, these connections exhibit a 64% greater capacity at the lower 5% exclusion value. Here again, using Student's *t* statistic at 31 and 11 degrees of freedom, respectively, we get 5th percentile strengths of 94.5 kN based on the smaller core tests and 155 kN for the larger ones. Assuming a predominately tension-type failure and an adjustment of 2.1 to account for duration of load and factor of safety, tests of the smaller cores support the derivation of a design capacity of 45 kN for a normal load duration (Appendix). By the same logic, the design capacity for the larger core joint would be 74 kN.

Joint Stiffness
Joint stiffness differences did not parallel strength differences for the two joint configurations. The slope of the load-displacement curves for the 12.7-cm test joints averaged 151 N/mm, with a 19% coefficient of variation. That for the 16.5-cm core joints averaged 175 N/mm, with a 15% coefficient of variation. In this case, the difference is only 15%. The linear range of the curve extended to at least 80% of the maximum load. The difference is attributed to a combination of larger section properties, the cross-section area bias for compression-parallel-to-the-grain deformation in the larger cores, and moisture differences.

Design Stress Derivation
Expected maximum strength and design stress for bearing parallel to the grain, tension, and shear are based on the dowel bearing capacity of coastal Douglas-fir (ANSI/AF&PA 1997), published values for clear wood (ASTM 1996), and the tensile capacity of sawn timber.

Following the National Design Specification for wood (ANSI/AF&PA 1997) and the strength ratio assumed for construction grade 4x4's, the normal load-duration design capacity of the dowel-nut connection would be 45 kN for a dowel bearing failure mode, 45 kN for a tensile failure, and 31.4 kN for a shear failure. The ASTM D2899 standard (ASTM 1995) for derivation of shear design stresses for round timbers, however, recommends a strength ratio of 0.75 (Wolfe 1989) in adjusting from small clear to full-sized round timber strength. Using this value and a coefficient of variation of 20% for round wood gives a design value of 67.2 kN (Appendix).

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 45 kN for normal load duration, shear, tension parallel to the grain, and bearing. Tension perpendicular to the grain, which also contributed to several of the 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 National Design Specification (ANSI/AF&PA 1997), gave predictions of maximum load that were close to what was measured (139 kN predicted, 132 kN measured).

CONCLUSIONS

- Dowel-nut strength in 12.7-cm-diameter Douglas-fir peeler cores had a mean strength of 132 kN with a coefficient of variation of 17%, while the strength of the dowel nut in 16.5-cm-diameter peeler cores averaged 175 kN with a 6% coefficient of variation.
- The design stress of Douglas-fir peeler cores is based on the assumption that the dowel nut is centered 7 diameters from the end of the peeler core. The derivation considers bearing capacity, tension and shear parallel to the grain (ASTM D2899), and tension perpendicular to the grain.
- Machining of the timber should be done under controlled conditions after the timber has been dried close to the expected ambient conditions.
- Holes for dowel nut should be oriented at more than 45° from the plane of any large drying checks
- Peeler cores should be graded to minimize effects of grain deviations and knots in the area of the joint
- Joint strength can be estimated on the basis of clear-wood strength and joint geometry with proper adjustment for ambient moisture conditions.

REFERENCES

ANSI/AF&PA 1997. National design specification for wood construction. American Forest and Paper Association/ American Wood council, 1111 19th St, NW, Suite 800, Washington DC 20036

ASTM 1993. Standard practice for establishing structural grades and related allowable properties for visually graded lumber. American Society for Testing and Materials, Standard D245-93, Vol. 4.10. 100 Barr Harbor Dr., W. Conshohocken, PA 19428-2959

ASTM 1995. Standard practice for establishing design stresses for round timber piles. American Society for Testing and Materials, Standard D2899, Vol. 4.10. 100 Barr Harbor Dr., W. Conshohocken, PA 19428-2959

ASTM 1996. Standard test methods for establishing clear wood strength values. American Society for Testing and Materials, Standard D2555, Vol. 4.10. 100 Barr Harbor Dr., W. Conshohocken, PA 19428-2959

FPL 1999. Wood handbook: Wood as an engineering material. USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Dr., Madison, Wisconsin 53705

Wolfe, R. 1989. Allowable Stresses for the upside-down timber industry. Proceedings for International Conference on Poles and Piles, Colorado State University, Ft. Collins, Colorado.

Wolfe, R., King, J., and Gjinolli, A.E., 2000. Dowel-nut connection in douglas-fir peeler cores. Submitted to Forest Products Journal, Marshall Ct., Madison, WI 53705

Table 1. Failure mode as a function of tension parallel to grain and shear versus compression bearing area

TEST SET	MC(%)	SG	Dowel/ Core ratio	TENSION AREA/COMPRESS. BEARING	SHEAR AREA/COMPRESS.	FAILURE MODE
Pilot tests-	25-30	0.43	0.25	2.5	17.7	Ductile failure*
			0.35	1.4	11.8	Ductile failure[a]
Pilot tests-Dry	9-11	0.43	0.35	1.4	11.8	Brash Failure[b]
Test of Dry	10	0.4	0.35	1.4	11.8	Brash failure[b]
	14	0.40	0.27	2.1	11.8	Ductile failure[a]

a Compression parallel to grain
b Combination of tension perpendicular to grain or compression parallel to grain with shear
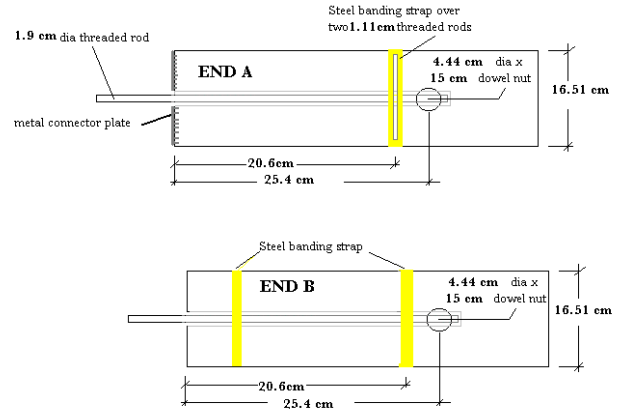
Figure 1. Dowel-nut connection detail

Figure 2. The 16.5-cm peeler core with different joint configurations on ends A and B

Figure 3. Predominant failure modes for dowel-nut connection

APPENDIX

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 1996)) and conventional design derivation procedures (AF&PA National Design Specification (ANSI/AF&PA 1997) and ASTM D245 (ASTM 1993)).

Assumed joint parameters

Nominal diameter of the dowel nut and the peeler core $\qquad$ $D_d = 44.45$ mm; $D_c = 127$ mm

Bearing length in timber core $\qquad$ $l = D_c - 25.4$ mm

Projected bearing area $\qquad$ $A_b = D_d \times D_c$

Tensile area $\qquad$ $A_t = \pi(0.5 \times D_c)^2 - A_b$

Dowel center end distance and shear area $\qquad$ $ND_c = 254$ mm ; $A_{shr} = (ND_c - 0.5D_c) \times D_c$

Bearing-parallel-to-the-grain failure

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

Dowel bearing strength (NDS table 8a) $\qquad$ $F_{es} = 37.92$ MPa

Expected ultimate bearing strength of test joint $\qquad$ $F_{es} \times D_d \times l \times (ND_c/7D_d) = 140.81$ kN

Design values assuming 7 D_d end distance:

Nominal design value (NDS) $\qquad$ $Z = D_d \times l \times (F_{es}/4)$ $\qquad$ $Z = 43.12$ kN

Design for wind $\qquad$ $Z_w = Z \times 0.005152$ kN $\qquad$ $Z_w = 49.59$ kN

Tension-parallel-to the-grain failure

NDS design stress for DF North construction grade 4×4 in
($\sim 100 \times 100$ mm) and design load capacity for 10-year dry use $\qquad$ $F_t = 6.55$ MPa ; $F_t \times A_t = 46.32$ MPa

Expected average ultimate strength
ASTM D245 assuming a COV of 20% $\qquad$ $(F_t \times 2.1 \times A_t)/(1 - 1.645 \times 0.2) = 144.97$ kN

Shear parallel to the grain failure

This failure mode appears as a block pushed between two shear panels

Shear area – two shear planes $\qquad$ $A_v = 2 \times A_{shr}$

NDS design shear stress for Douglas-fir North
construction grade 4×4 in ($\sim 100 \times 100$ mm) $\qquad$ $F_v = 0.655$ MPa

Design load capacity based on sawn lumber $\qquad$ $A_v \times F_v = 31.92$ kN

Green timber design value based on ASTM D2899 $\qquad$ $F_{vg} = 6.55(1 - 1.645 \times 0.13)/5.47 = 0.938$ MPa
(The factor 1/5.47 includes a 0.75 adjustment for SR, and 1/4 for DOL and FS)

Shear strength – average at 12% MC from ASTM D2555 $\qquad$ $F_{vd} = F_{vg} \times 1.48 = 1.390$ MPa

Load capacity $\qquad$ $F_{vd} \times A_v = 67.69$ kN