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Lateral Resistance of Ring-shank Nail Connections in Southern Pine Lumber

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LATERAL RESISTANCE OF RING-SHANK NAIL CONNECTIONS IN SOUTHERN PINE LUMBER

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ABSTRACT. *Ring-shank nails are used in engineered structures with lateral connection design values based on theoretically derived equations which were validated only for common nails. The goal of this study was to quantify the input parameters and lateral connection strength of several types of ring-shank nails in Southern Pine lumber and critically evaluate the applicability of the theoretical equations for ring-shank nails.*

Two sizes of galvanized and ungalvanized, hardened steel ring-shank nails from two manufacturers were studied. The hardened, ring-shank nails carried significantly higher loads than the common wire nails studied. Because the current method of determining yield load does not give adequate credit to hardened, ring-shank nails, an alternate method is proposed. ***Keywords.*** *Nail, Lateral, Ring-shank, Threaded, Annular.*

Due to their exceptional load-carrying capacity, ring-shank (or annularly threaded) nail connections are used extensively in demanding engineering applications such as post-frame construction. The design values for these connections in lateral loading, published in the National Design Specification (NDS) for Wood Construction (AF&PA, 1991), were validated historically for common nails but not for ring-shank nails.

Lateral nail connection design values in the NDS are calculated from theoretically derived equations based on the European yield model (EYM). Lateral nail connection capacities predicted by the EYM are divided by a connection normalization factor which calibrates the design values to historically published capacities. Input parameters to the EYM include nail bending yield strength and dowel bearing strength of lumber. EYM input parameters have not been quantified for ring-shank nails.

Experience in the post-frame industry indicates conservatism in lateral ring-shank nail design values, but test data for comparison of ring-shank nail connection performance with current design values are limited. Wills et al. (1996) outlined the need for quantifying inputs to the EYM specific to ring-shank nails as well as validating the EYM for ring-shank nail connections. No standards exist for the manufacture of ring-shank nails of the types studied here.

Finally, because most connection research has historically consisted of small sample sizes, little is known about the variability of lateral nail connection strength. As the design of wood structures continues to move toward reliability-based design, there exists a greater need for characterizing the variability of connection strength to quantitatively assess the safety and reliability of wood structures.

OBJECTIVES

The specific objectives of this research were to:

1. Characterize the nail bending yield strengths for nine types of nails including smooth-shank nails of 3.76 mm (0.148 in.) diameter, and ring-shank nails of 3.76 mm (0.148 in.) and 4.50 mm (0.177 in.) diameters (galvanized and ungalvanized, from two manufacturers).
2. Characterize the dowel bearing strength for each type of nail embedded in Southern Pine lumber.
3. Characterize the single-shear load-displacement behavior and maximum connection strengths for each nail type in Southern Pine lumber.
4. Compare connection test results with European yield model predictions which form the basis for design values published in the NDS.
5. Identify probability distributions which best describe the variability in lateral strength of ring-shank nail connections.

BACKGROUND

BASIS FOR DESIGN OF LATERAL NAIL CONNECTIONS

The 1991 NDS, a consensus standard for the design of wood structures, includes lateral nail connection design values based on the EYM (table 1). The EYM was originally developed for dowel type connectors by Johansen (1949) and applied specifically to common wire nail connections in the U.S. by Aune and Patton-Mallory

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Table 1. European yield model design equations for nail connection strength as they appear in the 1991 NDS (AF&PA, 1991)

Yield Mode	Equation*	Physical Description
I_s	$Z = \dfrac{D\, t_s\, F_{es}}{K_D}$	Wood yielding in side member
III_m	$Z = \dfrac{k_1\, D\, p\, F_{em}}{K_D (1 + 2\, R_e)}$	Wood yielding in both members Nail yielding in one member
III_s	$Z = \dfrac{k_2\, D\, t_s\, F_{em}}{K_D (2 + R_e)}$	Wood yielding in both members Nail yielding in one member
IV	$Z = \dfrac{D^2}{K_D}\sqrt{\dfrac{2\, F_{em}\, F_{yb}}{3(1 + R_e)}}$	Wood yielding in both members Nail yielding in both members

* Symbol definitions:

$$k_1 = -1 + \sqrt{2(1 + R_e) + \frac{2\, F_{yb}(1 + 2R_e)\, D^2}{3\, F_{em}\, p^2}}$$

$$k_2 = -1 + \sqrt{\frac{2(1 + R_e)}{R_e} + \frac{2\, F_{yb}(2 + R_e)\, D^2}{3\, F_{em}\, t_s^2}}$$

Z = lateral nail connection design value, N (lb) (the minimum calculated value controls the design load)
$R_e = F_{em}/F_{es}$
p = penetration of nail in main member (member holding point), mm (in.)
t_s = thickness of side member, mm (in.)
F_{em} = dowel bearing strength of main member, MPa (psi)
F_{es} = dowel bearing strength of side member, MPa (psi)
F_{yb} = bending yield strength of nail, MPa (psi)
D = nail diameter, mm (in.)
$K_D = 2.2$ for D < 4.3 mm (0.17 in.)
$K_D = 0.394D + 0.5$ for 4.3 mm < D < 6.4 mm
(= 10D + 0.5 for 0.17 in. < D < 0.25 in.)
$K_D = 3.0$ for D > 6.4 mm (0.25 in.)

(1986a,b). The model incorporates dowel bearing strength of wood, nail bending yield strength, and connection geometry to identify three main failure modes in single shear connections: (1) wood yielding in the side member; (2) wood yielding in both members with nail yielding in one member; and (3) wood and nail yielding in both members.

Dowel Bearing Strength

Wilkinson (1991) conducted dowel bearing strength tests for both parallel and perpendicular-to-grain loading using several nail diameters and lumber species groupings. Dowel bearing strength in wood, based on smooth-shank nail tests only, was determined to be dependent on specific gravity, with no statistically significant influence of nail diameter or wood grain angle. Wilkinson's (1991) empirically derived relationship is ($R^2 = 0.52$):

$$F_e = K \times G^{1.84} \qquad (1)$$

where
F_e = dowel bearing strength of the lumber, MPa (psi)
K = empirical constant, 114 MPa (16,600 psi)
G = lumber specific gravity based on oven dry weight and volume

Winistorfer (1995) provided further research data in support of equation 1 concluding that growth ring orientation has no practical effect on dowel bearing strength. While neither Wilkinson's equation nor Winistorfer's research were based on tests involving threaded nails, the 1991 NDS uses this relationship to assign dowel bearing strength values for all nail types (AF&PA, 1991).

Nail Bending Yield Strength

Nail bending yield strength data were obtained for several sizes of common nails by Loferski and McLain (1991). Nails were subjected to center-point loading at a constant displacement rate and the 5%-diameter-offset yield load was determined for each nail bend test as an estimate of the bending yield load of the nails. The 5%-diameter-offset yield load is defined as shown in figure 1. The straight line portion of the curve is offset by five percent of the nail diameter. The point at which this offset line crosses the load-displacement curve defines the yield load of the fastener.

Since Loferski and McLain's study, the 5%-diameter-offset method has become an accepted practice for determining yield load not only for nail bending tests, but also for dowel bearing and connection tests (ASTM, 1995a,b). The use of yield loads are an inherent part of the EYM, but the determination of yield load is subjective. The decision to use of the 5%-diameter-offset method was not based on an EYM specification, but rather on engineering judgment.

The 1991 NDS assumes a nail bending yield strength of 621 MPa (90,000 psi) from Loferski and McLain's common wire nail results (1991). Ring-shank nails are assumed to have a 30% higher nail bending yield strength than common wire nails because the NDS stipulates that ring-shank nails shall be made of high carbon steel and heat treated and tempered. This increase is based on engineering judgment rather than test data.

Lateral Nail Connection Research

While current design values for ring-shank nail connections are based entirely on the results of common nail tests, some research has been conducted on ring-shank nails. Stern (1969) summarized the results of research on a variety of fastener types in withdrawal and lateral loading. This compilation of several studies indicated that annularly threaded, hardened nails between 20d and 40d provided on average a 27% higher ultimate lateral strength than

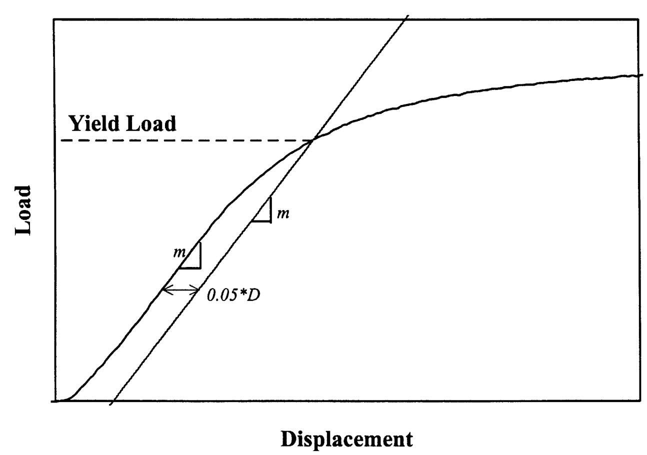

Figure 1–Illustration of 5%-diameter-offset method, where m equals the slope of the linear region and D equals the fastener diameter.

common nails of the same length and diameter. Sun and Bohnhoff (1990) conducted lateral tests on double-shear threaded nail connections. They found the load-displacement curve to be dependent on direction of loading with respect to grain orientation.

The results of these studies, while providing some insight into the performance of ring-shank nails in lateral loading, do not report connection yield load based on the 5%-diameter-offset method necessary for evaluating ring-shank nail performance relative to current design procedures. The connection yield loads reported by Stern (1969) and Sun and Bohnhoff (1990) were based on the load at 0.381 mm (0.015 in.) of connection displacement. The use of a load value at fixed displacement for estimating the connection yield load is documented in the 1974 *Wood Handbook*, and can be traced to earlier studies which based design values on load at the approximate proportional limit divided by an adjustment factor of 1.6 (*Wood Handbook*, 1955). This method of deriving design loads for lateral nail connections was used through the 1986 edition of the NDS (AF&PA, 1993).

Procedures

This research focused on quantifying the lateral strength of ring-shank nails of the types and sizes commonly used in post-frame construction. As a result, connections were tested using oil-quenched, hardened ring-shank nails connecting Southern Pine lumber in single-shear lateral loading.

Nail Specimens

The nails tested were composed of eight groups of ring-shank nails together with one group of 12d common nails for comparison purposes (table 2). The eight groups of ring-shank nails included two manufacturers, two nail sizes (16d and 20d), and two coatings: galvanized and ungalvanized. Suppliers A and B are manufacturers common to the post-frame industry as identified by an informal survey of builders in the industry. The 16d ring-shank nails and 12d common nails had the same shank diameter which provided a basis for isolating the combined effects of threads and steel quality on the lateral nail connection strength. Comparison of 16d and 20d ring-shank nails provided information on the change in lateral strength as a result of nail diameter. Galvanized nails were included for each ring-shank manufacturer and size due to the frequent use of galvanized products in construction. Galvanized nails from supplier A were mechanically galvanized while those from supplier B were hot-dipped galvanized.

After procurement of samples, nails with defects such as inconsistent threads, bent shanks, and off-centered heads were culled from the test groups. This culling process ensured that all nails tested met a basic level of quality which will facilitate the long-term goal of achieving standardization in ring-shank nail manufacturing. From the remaining nails, all test specimens were washed in mineral spirits, lightly brushed, and blown dry with compressed air to remove grease as specified in ASTM D1761 (ASTM, 1995c).

The nail shank diameter, outside thread diameter, total length, and threaded length were measured with digital calipers to the nearest 0.03 mm (0.001 in.). The inside thread diameter of the ring-shank nails, proving difficult to accurately measure with calipers, was measured with digital imaging equipment on the group of nails used for bending yield strength tests (20 nails per group). These data were used to assess thread characteristics for each nail group.

Table 2. Nail group nominal dimensions and average actual thread length with sample sizes for the three physical tests

Nail Group	Supplier	Nominal Dimensions: Diameter mm (in.)	Nominal Dimensions: Length mm (in.)	Average Actual Thread Length mm (in.)	Sample Sizes: Nail Bending	Sample Sizes: Dowel Bearing	Sample Sizes: Lateral Connection
12d common, ungalvanized	C	3.76 (0.148)	83 (3.25)	NA	20	20	40
16d ring-shank, ungalvanized	A	3.76 (0.148)	89 (3.50)	28.1 (2.74)	20	5	20
	B	3.76 (0.148)	89 (3.50)	61.5 (2.42)	20	5	40
16d ring-shank, galvanized*	A	3.76 (0.148)	89 (3.50)	69.9 (2.75)	20	5	20
	B	3.76 (0.148)	89 (3.50)	37.8 (1.49)	20	5	20
20d ring-shank, ungalvanized	A	4.50 (0.177)	102 (4.00)	73.2 (2.88)	20	5	20
	B	4.50 (0.177)	102 (4.00)	78.5 (3.09)	20	5	20
20d ring-shank, galvanized*	A	4.50 (0.177)	102 (4.00)	74.4 (2.93)	20	5	40
	B	4.50 (0.177)	102 (4.00)	74.2 (2.92)	20	5	20

* Galvanizing processes used were mechanical for supplier A and hot-dipped for supplier B.

Nail Bending Yield Strength Tests

A sample of 20 nails from each nail group was used to measure bending yield strength according to ASTM F1575 (ASTM, 1995a). This consensus standard requires that the nail be simply supported with a center-point load applied at a constant displacement rate of 6.4 mm (0.25 in.) per minute. Common nails were centered on the two supports, while threaded nails were placed such that the transition area between the unthreaded and threaded shank was as close to the center-point load as possible (ASTM, 1995a). Nail bending yield strength for each test was determined following procedures in the standard and was based on 5%-diameter-offset yield load. As required in the standard, stress was calculated based on the shank (unthreaded) diameter, which will result in more conservative estimates of nail bending yield strength than if root diameter were used.

Lumber Specimens

No.1 Southern Pine 2×4 dimension lumber was obtained from a local manufacturer for fabrication of connection test members as well as dowel bearing test specimens. The lumber was conditioned to a target equilibrium moisture content of 12% (dry-basis). The lumber for these tests was selected such that the specimens were as nearly clear and straight-grained as possible. Lumber with excessive knots, crook, or wane was not included in this study.

Dowel Bearing Strength Tests

Dowel bearing strength tests were conducted according to ASTM D5764 (1995b). Twenty tests were conducted on nails from each pennyweight class with five nails from each ring-shank nail group composing the specimens in the 16d and 20d sizes (table 2). Lumber specimens were matched across pennyweight class to isolate nail effects. This matching was achieved by cutting a specimen for a test from each pennyweight group from the same stick of lumber. For example, a 6 in. piece of lumber was cut for a test involving a 12d common nail, with two adjacent 6 in. pieces of lumber cut from the same piece along the length for tests involving a 16d ring-shank and 20d ring-shank nail.

All tests were conducted with loading parallel to the grain of the lumber, and with the threaded portion of nails covering the entire bearing length of the lumber. Moisture content and specific gravity were measured at the time of testing in accordance with ASTM D2395 (1995d). Yield load was determined from resulting load-displacement data using the 5%-diameter-offset method. The resulting yield load was converted to stress by dividing by the product of lumber thickness and nail shank diameter.

Lateral Connection Tests

Connection tests were conducted in accordance with ASTM D1761 as shown schematically in figure 2 (ASTM, 1995c). Multiple segments were cut from a single lumber specimen to provide the main members for nine tests (one nail from each of the nine nail groups). Similarly, side members were cut from one lumber specimen for tests from each nail group. Specific gravity coupons were cut from between two adjacent segments. The resulting specific gravity value was assigned to members on both sides. This system of matched sampling provided a means of obtaining similar wood properties across the nail groups.

Talcum powder was placed on contacting wood surfaces to reduce the static coefficient of friction (Pellicane and Sá Ribeiro, 1992). The side member was nailed perpendicular to the wide face while the main member accepted the point of the nail perpendicular to the narrow face. Hence, the resulting side member thickness was 38 mm (1.5 in.). The main member thickness of 89 mm (3.5 in.) was more than adequate for all nail lengths. Test fixture rollers, as shown in figure 2, counteracted the moment induced by eccentric loading inherent in this single shear connection (Liu and Soltis, 1984).

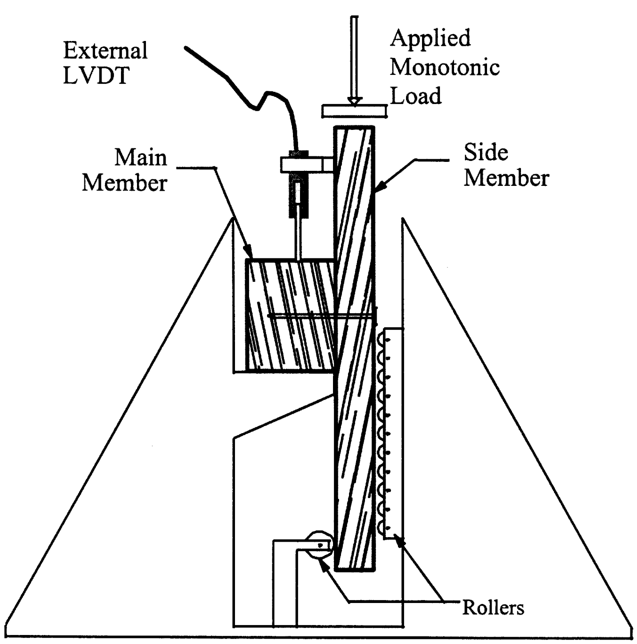

Figure 2–Schematic of single shear, lateral nail connection test. Rollers along side member resist moment caused by eccentricity of the connection. Side member thickness is 38.1 mm (1.5 in.). The nominal 2×4 main member accepts the point of the nail on its narrow face.

Connection test sample sizes for each nail group are shown in table 2. A minimum of 20 connections were tested for each of the nine nail types, while 40 tests were conducted in one nail group from each pennyweight class to facilitate fitting of probability distributions. Nails were hammer driven within 15 min of loading using a specially fabricated tool to ensure that the first 13 to 25 mm (0.5 to 1.0 in.) of driving occurred perpendicular to the lumber surface. All connections were loaded in compression at a constant displacement rate of 2.5 mm/min (0.1 in./min) for the first 13 mm (0.5 in.). Displacement rate was doubled for displacements above 13 mm. Load and displacement data were recorded continuously until the maximum load was achieved. Side member thickness and nail-head pull through were recorded for each connection at the conclusion of the test. Nail-head pull through was measured with calipers from the surface of the side member to the top of the nail head. Finally, moisture content and specific gravity were measured for each main and side member according to ASTM D2396 (1995d).

Test Results and Discussion

A summary of nail dimensional and thread characteristics, nail bending yield strength tests, dowel bearing strength tests, and connection tests is presented next. The results of these tests are needed to evaluate the EYM. Finally, alternative yield definitions are discussed and probabilistic representations of lateral connection strength are presented.

Nail Bending Yield Strength

The subset of 20 nails from each group used for nail bend tests was sampled from the same box of nails used for connection tests. The average shank diameter of the nine nail groups tested, as shown in table 3, never fell below the nominal diameter given in table 2. Variation about the mean was minimal, with a maximum coefficient of variation (CV) of 1.2%. The thread depths of the ring-shank nails exhibited greater variability resulting in CVs within groups ranging from 11.3% to 30.0%.

The average nail bending yield strength for each group is given in table 3. The 12d common nail group average of 639 MPa (92,740 psi) was in close agreement with the 1991 NDS value of 621 MPa (90,000 psi) (AF&PA, 1991). All the ring-shank nail groups, with the exception of Supplier A's galvanized 16d and 20d nails, were well above the value of 793 MPa (115,000 psi) assumed in the 1991 NDS tables. These six groups averaged 85% higher F_{yb}

Table 3. Average ring-shank nail dimensional properties and nail bending yield strength (F_{yb}) for 20 replications in each group

Nail Group	Sup-plier	Shank Diameter mm	Shank Diameter (in.)	COV* %	Thread Depth† mm	Thread Depth† (in.)	COV* %	F_{yb} MPa	F_{yb} (psi)	COV* %
12d common, ungalvanized	C	3.81	(0.150)	0.0	NA		NA	639	(92700)	2.4
16d ring-shank, ungalvanized	A	3.78	(0.149)	0.2	0.16	(0.006)	27.8	1370	(198000)	3.5
	B	3.84	(0.151)	0.7	0.24	(0.009)	11.3	1300	(189000)	5.4
16d ring-shank, galvanized	A	3.86	(0.152)	1.2	0.26	(0.010)	16.4	650	(93700)	5.3
	B	3.80	(0.150)	0.3	0.23	(0.009)	13.5	1110	(161000)	3.4
20d ring-shank, ungalvanized	A	4.50	(0.177)	0.4	0.18	(0.007)	30.0	1120	(162000)	12.3
	B	4.51	(0.178)	0.4	0.26	(0.010)	17.6	1120	(163000)	7.4
20d ring-shank, galvanized	A	4.58	(0.180)	0.6	0.18	(0.007)	29.8	638	(92500)	4.0
	B	4.61	(0.182)	0.5	0.22	(0.008)	19.8	1070	(155000)	3.3

* COV = standard deviation ÷ mean.

† Thread depth = ½ × (outside thread diameter – inside thread diameter).

than the 12d common nail group—well above the 30% increase assumed in the 1991 NDS.

The F_{yb} values for the galvanized nails from Supplier A were similar in strength to the 12d common nails, suggesting that these nails were not oil-quenched hardened and possibly not even high-carbon steel. Galvanized nails from Supplier B exhibited slightly lower F_{yb} than ungalvanized nails from the same supplier, possibly due to tempering effects in the hot-dip galvanizing process. It is unlikely that the F_{yb} reduction observed for Supplier A was due to galvanizing since a mechanical galvanizing process was used.

DOWEL BEARING STRENGTH

The average dowel bearing strengths for the 12d common, 16d ring-shank, and 20d ring-shank nail groups were 47.2 MPa (6840 psi), 47.4 MPa (6870 psi), and 41.7 MPa (6050 psi), respectively. The CVs for these groups were 20.5%, 18.8%, and 17.6%. Use of Duncan's Multiple Range Test at a significance level of 10% showed no difference in the means of the 12d common and 16d ring-shank groups, while the 20d ring-shank group was statistically different from both the 12d and 16d groups. This statistical comparison leads to the conclusion that there is a diameter effect but no thread effect on dowel bearing strength.

As a means to better estimate dowel bearing strength as an input to the EYM for the specific nails tested in this study, a regression model was developed to relate the variability of dowel bearing strength values to specific gravity and nail diameter. The average specific gravity based on oven-dry weight and volume for the 20 pieces of lumber was 0.572 with a minimum value of 0.435 and 0.707 maximum. Simple linear regression was performed on the data after a logarithmic transformation to obtain the following relationship (R^2 = 0.78):

$$F_e = k \times G^{1.36} \times D^{-0.73} \qquad (2)$$

where

F_e = dowel bearing strength, MPa (psi)
k = 264 (SI units)
= 3670 (English units)
G = specific gravity based on oven dry weight and volume
D = nail shank diameter, mm (in.)

Evaluating equation 1 using the average specific gravity from these tests (0.572) yields a dowel bearing strength of 40.8 MPa (5940 psi), lower than each of the three averages for the nail groups investigated in this study. The inclusion of perpendicular-to-grain tests in Wilkinson's study is a possible reason for the lower value. While Wilkinson found no statistically significant effect of grain angle on dowel bearing strength of nails, bolt dowel bearing strength in perpendicular-to-grain loading is substantially lower than parallel-to-grain values (AF&PA, 1991).

CONNECTION TESTS

Average connection loads at fixed displacement levels are summarized for each nail group in table 4. Displacement levels at which average loads are reported range from 0.25 mm (0.01 in.) to 13 mm (0.5 in.). Figure 3 displays these average loads graphically for several displacement levels in addition to showing the 5%-diameter-offset yield load, predicted yield load, and maximum load.

Table 4. Average connection loads by nail group at nine displacement levels

		δ = 0.25 mm (0.01 in.)			δ = 0.38 mm (0.015 in.)			δ = 0.64 mm (0.025 in.)		
		Load		CV	Load		CV	Load		CV
Nail Group	Supplier	N	(lbs)	%	N	(lbs)	%	N	(lbs)	%
12d common, ungalvanized	C	640	(144)	15.3	762	(171)	14.5	926	(208)	13.2
16d ring-shank, ungalvanized	A	597	(134)	13.9	733	(165)	13.4	957	(215)	12.5
	B	541	(122)	27.3	684	(154)	23.7	923	(208)	19.7
16d ring-shank, galvanized	A	518	(117)	22.4	632	(142)	21.7	813	(183)	19.9
	B	496	(112)	32.2	612	(138)	29.5	834	(188)	23.5
20d ring-shank, ungalvanized	A	703	(158)	19.5	865	(194)	18.1	1140	(255)	15.5
	B	637	(143)	18.8	788	(177)	16.2	1030	(232)	13.3
20d ring-shank, galvanized	A	695	(156)	23.9	853	(192)	21.7	1110	(249)	19.0
	B	771	(173)	24.7	932	(210)	23.0	1200	(270)	20.7

		δ = 1.3 mm (0.05 in.)			δ = 2.5 mm (0.10 in.)			δ = 3.8 mm (0.15 in.)		
		Load		CV	Load		CV	Load*		CV
Nail Group	Supplier	N	(lbs)	%	N	(lbs)	%	N	(lbs)	%
12d common, ungalvanized	C	1140	(256)	11.9	1340	(300)	11.5	1480	(332)	10.6
16d ring-shank, ungalvanized	A	1360	(307)	11.0	1820	(409)	9.6	2100	(472)	9.0
	B	1360	(306)	15.4	1880	(423)	11.8	2160	(486)	11.0
16d ring-shank, galvanized	A	1120	(251)	15.6	1420	(320)	12.9	1600	(360)	12.7
	B	1240	(280)	16.4	1700	(381)	12.6	1940	(436)	11.6
20d ring-shank, ungalvanized	A	1630	(365)	12.0	2220	(499)	10.8	2600	(583)	10.7
	B	1440	(324)	10.3	1970	(443)	10.5	2340	(526)	10.7
20d ring-shank, galvanized	A	1550	(348)	14.2	1990	(446)	11.0	2220	(500)	11.0
	B	1690	(379)	17.5	2310	(520)	15.1	2670	(600)	13.7

		δ = 5.7 mm (0.225 in.)			δ = 7.6 mm (0.30 in.)			δ = 13 mm (0.50 in.)		
		Load*		CV	Load*		CV	Load*		CV
Nail Group	Supplier	N	(lbs)	%	N	(lbs)	%	N	(lbs)	%
12d common, ungalvanized	C	1600	(360)	10.4	1660	(373)	10.8	1730	(390)	9.8
16d ring-shank, ungalvanized	A	2420	(543)	9.3	2690	(604)	9.8	3220	(723)	10.9
	B	2440	(549)	11.3	2710	(610)	12.4	3430	(770)	12.9
16d ring-shank, galvanized	A	1860	(417)	13.8	2160	(484)	13.8	2840	(638)	12.0
	B	2190	(492)	12.5	2420	(544)	13.2	2950	(662)	13.8
20d ring-shank, ungalvanized	A	2990	(672)	12.1	3310	(744)	13.5	4170	(937)	10.8
	B	2700	(605)	11.1	2980	(670)	11.8	3770	(848)	11.5
20d ring-shank, galvanized	A	2500	(563)	11.8	2780	(624)	13.0	3530	(794)	13.2
	B	3010	(676)	13.3	3300	(741)	13.4	4090	(920)	12.3

* The load at fixed displacement for a given connection test was used in the average for the group only when the load value occurred prior to maximum load.

Figure 4(a) shows load-displacement curves for two tests of nail connections with the same shank diameter. Figure 4(b) illustrates how the 5%-diameter-offset method is used for analyzing connection data. Since both connections have similar slopes in the initial linear portion of the curve, the resulting yield loads based on the 5%-diameter-offset method are very similar. Naturally, the initial portion of the load-displacement curve for all test

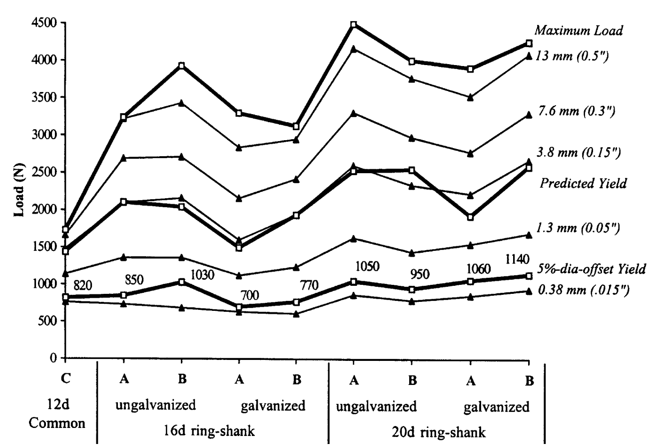

Figure 3–Average loads at given displacement compared to maximum, predicted yield, and observed yield loads. Average 5%-diameter-offset yield loads (N) are listed by group.

groups was dominated by lumber resistance to crushing (dowel bearing strength). Since lumber was matched across nail groups, there is little difference in average loads at low displacement levels (fig. 3). However, for higher displacements, the nail bending yield strength has more effect on connection performance, and distinctions between nail groups become more evident.

As illustrated in figure 4(a), the 16d ring-shank nail takes considerably more load than the 12d common nail as displacement increases. For the common nail, interaction between nail embedment in the lumber and yielding of the steel causes the nail shank to bend. At this point, connection strength begins to be dominated by withdrawal resistance of the nail. This process occurs as the curve "flattens out" and results in the common nail connection maintaining a fairly constant load level for displacements in excess of approximately 5 mm (0.2 in.).

The combination of higher nail bending yield strength and superior withdrawal resistance of ring-shank threads for the 16d specimen results in much different connection behavior. Higher nail bending yield strength causes the load-displacement curve to reach higher loads before showing signs of flattening out. As the lumber and steel begin to yield at larger connection displacements, the ring-shank threads resist withdrawal and act to draw the wood members together. For further connection displacement to occur, one of five possible failure modes must begin to dominate connection behavior: (1) nail withdrawal from the main member (as typically occurs for common nails in laterally-loaded connections); (2) nail-head pull-through in the side member; (3) splitting of either the main or side member; (4) bearing failure of the wood; or (5) shear failure of the nail. Since ring-shank nails with well defined threads exhibit exceptional resistance to withdrawal loading (Skulteti et al., 1996), they can withstand much larger connection loads than common nails before nail withdrawal from the main member begins to occur.

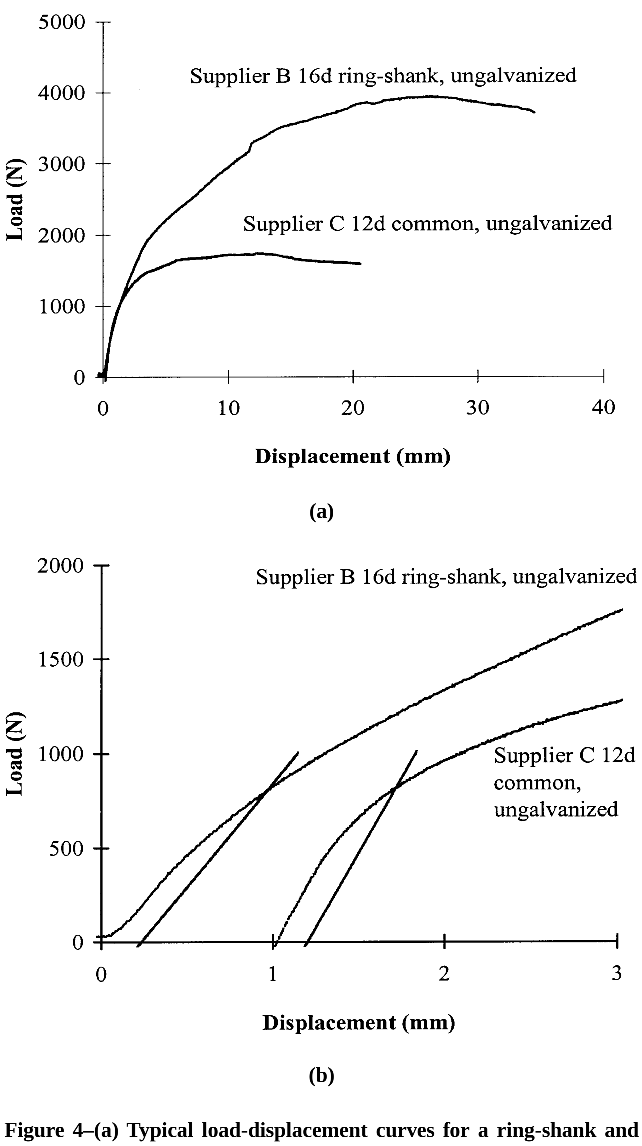

Figure 4–(a) Typical load-displacement curves for a ring-shank and common nail. (b) Initial linear region; common nail curve is offset 1 mm for clarity of presentation.

The average maximum loads given in table 5 show that ring-shank nail connections have roughly twice the strength of common nail connections. The breakdown of connection failure modes illustrates the different connection behavior associated with ring-shank nails. Failure of common nail connections was dominated by nail withdrawal; whereas, other failure modes were observed for ring-shank nail connections due to greater withdrawal resistance and higher bending yield strength.

Evaluation of Design Values

Observed connection yield loads (based on the 5%-diameter-offset method) were compared to EYM estimates using input parameters based on nail bending and dowel bearing tests. Nail bending yield strength inputs were based on the average for each group, while dowel bearing strength values were based on actual nail diameter and main and side member specific gravity using equation 2. Average specific gravity values by nail group for main and side members are shown in table 6.

Figure 3 illustrates that 5%-diameter-offset yield loads were well below the predicted yield loads for all groups. Upon closer comparison of the connection load-displacement curves with the nail bending yield strength curves, it became obvious that the 5%-diameter-offset method defined a point at which the wood in the connection was yielding, but the hardened steel nail was not. However, nail yielding typically occurred at a connection displacement of approximately 3.8 mm (0.15 in.), as indicated by a distinct change in the slope of the load-displacement curves. If connection yield point is defined as the load corresponding to a fixed displacement of 0.15 in., the EYM model predicts lateral connection strength for the connections tested with remarkable consistency as depicted in figure 3. It should be noted that EYM theory does not dictate *how* connection yield point is determined, and that the 5%-diameter-offset method has not been validated for nails nor is it an inherent part of EYM theory. In fact, the validation study of Aune and Patton-Mallory (1986b) on common nails used a yield point definition similar to that proposed here.

Adopting a "fixed displacement method" for defining the connection yield point (in lieu of the 5%-diameter-offset method) would provide the added benefit of eliminating the ambiguity of trying to find a "linear region" in the initial portion of inherently nonlinear load-displacement curves for nailed connections. It is unknown whether this method is

Table 5. Connection maximum loads and dominant failure modes

Nail Group	Supplier	No. Tests	Maximum Load Mean N	(lb)	CV (%)	Disp. at Max. Load Mean mm	(in.)	CV (%)	Dominant Failure Mode* (%) WD	HPT	SPL	NSH
12d common, ungalvanized	C	40	1730	(389)	12.8	2.34	(0.526)	42.9	95.0	0.0	5.0	0.0
16d ring-shank, ungalvanized	A	20	3240	(729)	12.7	2.78	(0.624)	26.2	5.0	15.0	5.0	75.0
	B	40	3930	(883)	13.5	3.63	(0.815)	24.2	40.0	37.5	7.5	15.0
16d ring-shank, galvanized	A	20	3300	(741)	13.6	3.47	(0.780)	22.4	75.0	20.0	5.0	0.0
	B	20	3130	(703)	13.8	2.86	(0.643)	19.4	85.0	10.0	5.0	0.0
20d ring-shank, ungalvanized	A	20	4500	(1010)	18.2	3.49	(0.783)	36.6	50.0	25.0	25.0	0.0
	B	20	4010	(901)	26.6	3.19	(0.718)	44.5	15.0	20.0	45.0	20.0
20d ring-shank, galvanized	A	40	3910	(878)	21.4	3.32	(0.746)	34.2	47.5	22.5	30.0	0.0
	B	19†	4260	(958)	17.9	3.13	(0.703)	33.6	47.4	15.8	36.8	0.0

* WD = Withdrawal of the nail from the main member. This failure mode was not observable during testing, but it is assumed that withdrawal occurs to some degree in all connection tests. WD was deemed dominant only when none of the other three modes dominated.
HPT = nail head pull-through on the side member. Measurement of 2.54 mm (0.1 in.) or more was considered HPT dominated failure mode.
SPL = main member splitting.
NSH = shear failure of the nail.
† One connection specimen of the total of 20 split during fabrication and was not tested.

Table 6. Average specific gravity by nail group for connection test main and side members

Nail Group	Supplier	Sample Size	Average Specific Gravity* Main Member	Side Member
12d common, ungalvanized	C	40	0.586	0.564
16d ring-shank, ungalvanized	A	20	0.594	0.571
	B	40	0.585	0.562
16d ring-shank, galvanized	A	20	0.596	0.574
	B	20	0.589	0.574
20d ring-shank, ungalvanized	A	20	0.584	0.571
	B	20	0.587	0.571
20d ring-shank, galvanized	A	40	0.573	0.561
	B	20	0.595	0.571

* Specific gravity is based on oven dry weight and volume.

appropriate for a broader range of nail sizes and diameters. Additional tests are being conducted at the U.S. Forest Products Laboratory on a range of nail sizes and species groups to assess whether a connection displacement of 3.8 mm (0.15 in.) provides an adequate definition of yield point for all types of nailed connections.

Validating the accuracy of the European yield model for nails is important for predicting design values for *any* combination of nail size, lumber species, and connection geometry. However, the EYM is not intended to predict lateral connection behavior after the yield point is reached. Hence, some other method is required to account for the superior *ultimate* strength of lateral ring-shank nail connections compared to that of common wire nails. Any benefit realized as a result of superior ultimate strength must be accompanied by manufacturing standards for thread and steel quality.

The average ultimate strength of the 12d common nail connections in this study is 17% greater than its connection yield strength at 3.8 mm (0.15 in.) displacement (tables 5 and 6). If similar values are calculated for the ring-shank nail groups, the increases range from 54 to 106%. Hence, there is more reserve capacity in hardened, threaded nail connections as compared to common nails since these nails retard withdrawal of the nail from the main member and allow other types of failure mechanisms (fig. 3). Some increases in nail capacities may be appropriate for hardened, threaded nails as a result of greater ratios between ultimate strength and load at 3.81 mm (0.15 in.) of displacement. Ongoing tests at the U.S. Forest Products Laboratory should indicate whether a similar increase is appropriate for a broader range of nail sizes and lumber species. Of course, any adjustment should be predicated on an effective quality assurance program within the nail industry to guarantee specified levels of nail bending yield strength and thread characteristics.

Probabilistic Representation

Characterizing the best-fitting probability distributions for ring-shank nail connection strength, while not directly applicable to the current design methods for nail connections, is important information as wood structural design moves toward a reliability basis. The three nail groups with 40 connection test replications (table 2) were used for probabilistic characterization of connection maximum loads. These three groups were chosen to include samples across all three suppliers, both shank types, both nail sizes, and both coatings (galvanized and ungalvanized).

Probability density functions considered in this analysis were limited to the two-parameter Weibull, two-parameter lognormal, and normal distributions. These distributions were chosen based on their frequent use in characterization of wood strength properties and acceptance in reliability analyses. The maximum likelihood technique was used to estimate parameters with computer routines described by Worley et al. (1990). Chi-square (χ^2) and Kolmogorov-Smirnov (KS) goodness-of-fit tests were used in conjunction with visual appraisal to identify best fitting distributions. The parameters of the best fitting density functions are given in table 7.

Summary and Conclusions

The National Design Specification (NDS) for Wood Construction uses the European Yield Model (EYM) as the basis for design of laterally loaded nail connections (AF&PA, 1991). Inputs to this model as well as validation of model results are based on tests involving common wire nails, while the design methods apply to deformed shank nails including annularly threaded (ring-shank) nails. This

Table 7. Comparison of three probability density functions for connection ultimate load data in N (lb)

Nail Group	Supplier	Distribution	Probability Distribution Parameters: Scale		Shape	
12d common, ungalvanized	C	2-P Lognormal	7.45	(5.95)	0.133	(0.133)
16d ring-shank, ungalvanized	B	2-P Lognormal	8.27	(6.78)	0.131	(0.131)
20d ring-shank, galvanized	A	Normal*	826	(186)	3910	(878)

* The scale column for the normal distribution lists the standard deviation, while the shape column provides the mean.

research focused on investigating the lateral performance of ring-shank nails in Southern Pine lumber and equating that performance to predictions of the EYM.

The hardened, ring-shank nails tested in this study were found to have significantly higher nail bending yield strength than the common nails tested in this study (table 3). The average of the galvanized, ring-shank nail groups from Supplier A were similar to the average nail bending yield strength of the 12d common group suggesting that these nails were not oil-quenched hardened during manufacturing. The remaining six hardened, ring-shank nail groups averaged 85% higher nail bending yield strength than the 12d common nail group—well above the 30% increase assumed in the NDS (AF&PA, 1991).

Dowel bearing tests were conducted to better quantify this property as an input to the EYM for the combination of nail types and lumber used. A regression equation was developed from the test data incorporating lumber specific gravity and nail diameter.

EYM estimates of connection yield strength were calculated for each connection tested using nail bending and dowel bearing strength estimates as well as connection geometry information. Based on 5%-diameter-offset yield load, actual connection performance fell well below EYM estimates. The 5%-diameter-offset yield load method was difficult to apply to load-displacement curves because the method assumes the curve will have an initial linear region which was not observed with the nailed connections tested in this study. The initial portion of load-displacement curves was dominated by localized lumber crushing prior to nail yielding. Therefore, the 5%-diameter-offset yield load method was not satisfactory for the nails tested in this study.

A “fixed displacement” method is proposed that could be used to define yield point, as an alternative to the 5%-diameter-offset yield load method. Based on the nails and lumber used in this study, a displacement level of 3.8 mm (0.15 in.) seems appropriate, incorporating nail bending yield strength and better reflecting estimates of the EYM. Additional tests are underway at the U.S. Forest Products Lab to evaluate this recommendation for other nail types, sizes, and lumber species.

The ratio between average ultimate strength and connection yield strength at 3.8 mm (0.15 in.) displacement for the ring-shank nail groups ranged from 54 to 106% while the ratio for the 12d common nail group was 17%. As a result, some increase in lateral nail connection capacities may be appropriate for hardened, threaded nails. Adoption of any increases in performance of threaded, hardened steel nails must be accompanied by standardization in nail manufacturing. This type of standardization should address assurance of steel and thread quality which have shown to be critical to connection performance.

Finally, the two-parameter lognormal probability density function was judged to best fit the 12d common and 16d ring-shank maximum connection strengths, while the normal distribution was the best-fitting density function for the 20d ring-shank group. This information will help provide a basis for probabilistic characterization of nail connection strength as development continues on reliability-based design of wood structures.

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