Withdrawal strength of bright and galvanized annulary threaded nails

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Introduction

Threaded nails, initially used in shoe, automobile and boat industries (Stern 1950a), have expanded into wood and post frame construction markets. Stern (1956) advocated their use in wood construction because of the increased withdrawal strength and extensively researched the use of threaded nails in pallets. Based on post frame construction experience, Geisthardt et al. (1991) reported that published design values for large threaded nails are conservative. It is speculated that the conservative design values result from the lack of experimental data for large nails and spikes and the lack of standardization of thread characteristics.

Recently ASTM F1667, Table 45 (ASTM 2006) was modified to standardize the characteristics of annularly threaded nails. The standardization of a specific type of annularly threaded nails, called post-frame ring shank nails, creates the opportunity for both manufacturers and designers to take advantage of the increased withdrawal design capacity of these types of nails. This report details a research study investigating the withdrawal strength of nails manufactured to the ASTM F1667 post-frame ring shank standard.

Background

Threaded Nails

Threaded nails are classified as either annular (ring shank) or helical, based on the thread crest orientation. The threads of annular nails are perpendicular to the nail axis; those of helical nails are typically aligned at angles between 30° and 70° to the nail axis (**Figure 1**). Threads are manufactured by rolling annular or helical deformations longitudinally onto the shank of a smooth nail, resulting in a slightly smaller root diameter than that of smooth nails of comparable pennyweight (Wills et al. 1996).

Smooth shank nails resist withdrawal forces by the frictional forces between the wood fibers and nail shank. Frictional forces are greatest just after driving, but eventually the fibers surrounding the nail relax, causing withdrawal strength to crease. Wood relaxation may be compounded if lumber dries and shrinks over time as a result of changing moisture conditions.

Gahagan and Scholten (1938) noted a 57% reduction in withdrawal load for 7d common nails 105 days after nails were driven into matched specimens. Contrastingly, threaded nails resist withdrawal forces by friction and by wood fibers lodged between the threads. When threaded nails are driven wood, the wood fibers separate and lodge between the thread crests. These lodged fibers must be broken before threaded nails are withdrawn from wood; therefore, relaxation and shrinkage have little effect on strength. Researchers (Mack 1960; Moehler and Ehlbeck 1973) have shown an increase in withdrawal strength of threaded nails driven into green lumber as the lumber dried.

One concern with threaded nails is the effect of galvanized coatings. Hot dip galvanizing process may change withdrawal strength by filling and smoothing thread valleys, especially in annular nails (Feldborg and Johansen 1972, Skulteti and others 1997).

Early studies on threaded nails were limited and focused on fundamental mechanics and moisture effects. Stern has investigated the withdrawal strength of various types of threaded nails. His early work focused on determining the effectiveness of threaded nails as compared to that of smooth shank nails for a variety of parameters: diameter, length, carbon content, coating, and "driveability" (Stern 1950a.b. 1956).

As the engineering profession moves toward a load and resistance factor design procedure based on reliability concepts, large replication databases are needed to characterize resistance distributions. Two coordinate studies, (Skulteti and other 1997, Rammer and others 2001) were undertaken to evaluate the underlying probabilistic distributions withdrawal strength distributions of threaded nails and make recommendations for design capacity.

Skulteti et al. (1997) determined the withdrawal strength of annularly threaded nails in Southern Pine lumber for relatively large sample sizes (n = 60). They investigated the effects of nail diameter and galvanizing on the immediate withdrawal strength of three sizes of annularly threaded nails and compared strength values to that of common

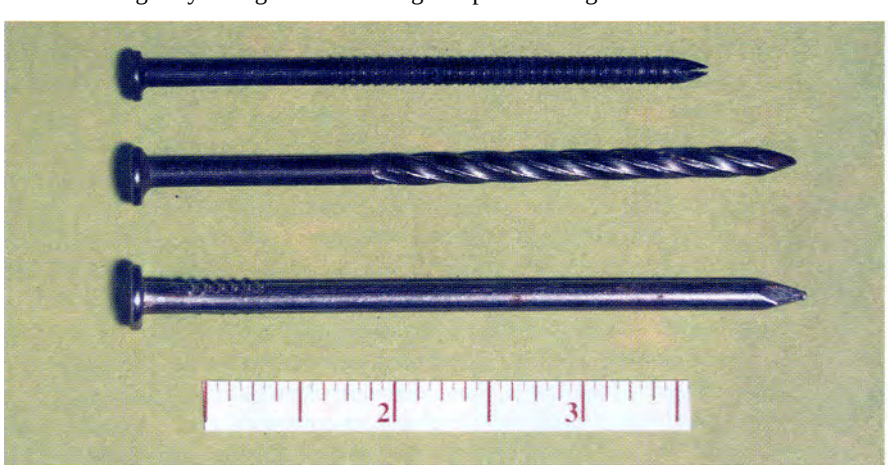

Figure 1. Nail classification (top to bottom): annularly threaded, helically threaded and smooth.

nails. Researchers concluded that annularly threaded nails have withdrawal capacities twice as great as those of smooth shank nails of similar diameter. Using their data and standard practice for calculating allowable values, calculated design values for annularly threaded nails were 30% higher than National Design Specifications (NDS) for Wood Construction (AF&PA 2005) published levels. These researchers showed that withdrawal strength can be modeled by either the Weibull or lognormal distributions. They also advocated standardization of thread characteristics before allowing design value increases for annularly threaded nails.

Rammer and others (2001) investigated the effects of nail diameter, nail type, and galvanizing on the immediate withdrawal strength of annularly threaded in Spruce-Pine-Fir and Douglas-Fir. Based on this study, it was noted that the current NDS design procedures for withdrawal strength underestimates the performance of threaded nails. The greatest differences were observed for annularly threaded nails. Rammer and others concluded that design withdrawal values for annularly threaded nails could be increased by 50% for the full range of specific gravity values examined (**Figure 2**).

Expressions for the mean withdrawal strength of annularly threaded nails were derived using the same format as the current NDS expression (2) with all the test data generated. For annularly threaded nails a withdrawal strength expression would be

$$W=6{,}207 \quad G^{1.38}D \qquad ①$$

where W = allowable withdrawal design strength per unit length of nail penetration (N/mm); G = specific gravity of the member holding the nail point, based on oven-dry weight and oven-dry volume; D = shank diameter of nail (mm).

Finally, the manufacturing source of the annularly threaded nails had no effect on withdrawal strength and, based on five different groups with 50 replications each, a lognormal distribution is the underlying distribution for withdrawal strength. The effect of galvanizing with of these two studies will be discussed later.

Skulteti and others (1997) and Rammer and others (2001) both indicated that for bright, annularly threaded nails a minimum 30% increase in the design withdrawal capacities could be justified once the thread characteristics of annularly threaded nails are standardized. The increase may be greater for lower specific gravity wood (SPF and Douglas Fir) than higher specific gravity wood (Southern Pine).

Galvanizing

To inhibit rust development in damp environments and preservative treated lumber, galvanized coatings are applied to nails. Galvanized coatings are shown to influence the withdrawal strength of smooth shank nails by altering the surface texture (Ehlbeck 1976).

Werner and Siebert (1991) investigated the effect of galvanized coatings and fabrication on the withdrawal performance of nails. They concluded that fabrication tolerances strongly influence withdrawal performance and developed an empirical relationship that relates withdrawal strength to shank diameter and specific gravity. Threads, steel type, and coating interact with the wood to determine the connection withdrawal strength.

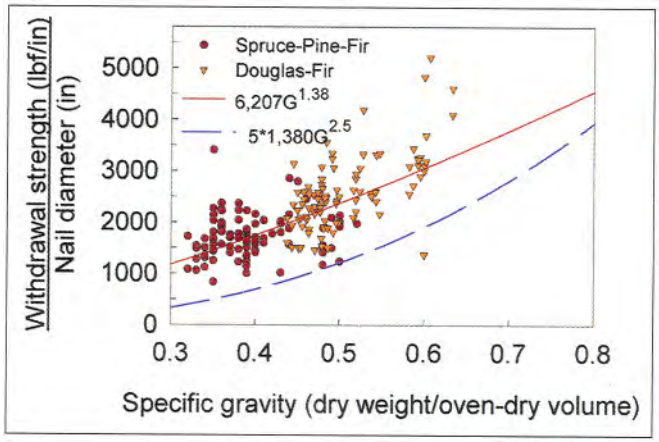

Figure 2. Withdrawal strength divided by shank diameter as a function of specific gravity for annularly threaded nails (Rammer and others 2001).

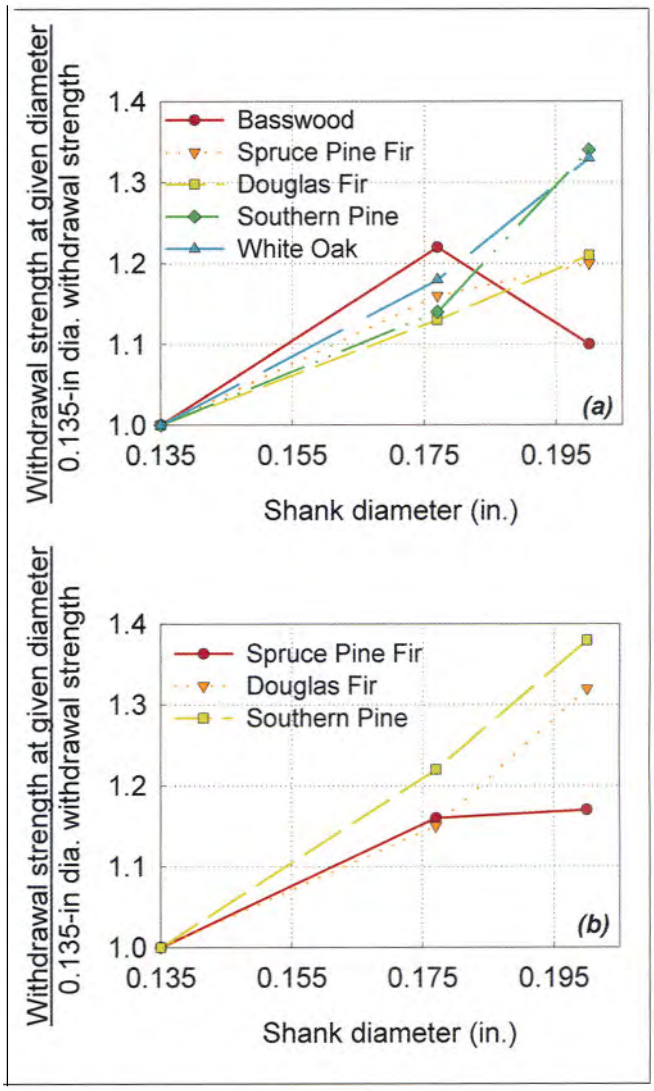

Figure 3. Ratio of average withdrawal strength relative to the 0.135-in. shank diameter withdrawal strength for each wood species for (a) bright and (b) galvanized annularly threaded nails.

Furthermore, galvanized coatings may change withdrawal strength by filling and smoothing thread valleys, especially in annular nails (Feldborg and Johansen 1972).

For two different manufactured annularly threaded nails in Southern Pine, Skulteti and others (1997) found about an 8% decrease in the withdrawal strength of galvanized nails compared to matched bright nails. For helically threaded nails, Rammer and others (2001) found that galvanizing had a statistically significant effect for nails driven in Southern Pine, while galvanizing had no significance effect for nails driven in Spruce-Pine-Fir. The greatest mean difference in withdrawal strength between galvanized and bright nails was 18%.

Withdrawal Relationships, Design Provisions, and Standards

Two approaches are approved to assign withdrawal strength design values. For building construction, design values are assigned by the NDS. For pallet construction, design values are assigned using an American Society of Mechanical Engineers (ASME) procedure. Each method is presented in the following section along with other relevant withdrawal relationships.

Design values currently published in the NDS (AFPA 2005) are based on research using bright, common degreased smooth shank nails. The original work most focus on 7d smooth shank nails but additional sizes were included to investigate nail size effects (Gahagan and Scholten, 1938). Based on this research, the following expression was developed to relate withdrawal strength, specific gravity, and nail diameter:

$$W = KG^{2.5} D \qquad ②$$

where W = allowable withdrawal design strength per unit length of nail penetration (N/mm); G = specific gravity of the member holding the nail point, based on oven-dry weight and oven-dry volume; D = shank diameter of nail (mm); and K = constant factor. When K is taken as 1,380 lbf/in2, (2) represents the mean of the experimental ultimate withdrawal strength divided by a factor of 5. This factor, which is embedded in K, accounts for test conditions, safety, duration of load, and experience (Commentary 1993). When K is taken a 6,900 lbf/in2 (2) represents the immediate withdrawal strength.

This expression (2), for smooth shank nails, has been the basis of nail withdrawal design since 1944. Several withdrawal studies have been conducted, but no modifications had been proposed to Eq. (2) until recently. In 1962, the NDS addressed withdrawal design values for threaded nails by assigning the values for threaded nails the same level as those for common nails of the same pennyweight class.

In 1968, changes were made to the procedure to account for the common nail wire diameter increasing from 20d to 60d, whereas the threaded nail diameter remains constant at 4.50 mm in the 20d-60d range (Commentary 1993).

Comparison of Eqn (l), for annularly threaded nails, and (2), using the ultimate withdrawal strength factor (6,900 lbf/in2) clearly indicates that the current NDS expression under predicts the mean trend for both tested wood species. Both expressions show that the dependence on specific gravity but this dependence is lower for threaded nails as compared to the 5/2 power in for smooth nails (2).

McLain (1997) compiled 1,914 withdrawal tests of common nails from reports published since the 1930s. A regression analysis of these data led to a newly proposed expression to predict average withdrawal strength for common nails

$$W = CG^{2.24} D^{0.84} \qquad ③$$

where C = empirical constant that equals 8,270 lbf/in2 and a percent standard error (PSE) of the estimator of 30.1 compared to a percent standard error of the estimator of 35.2 for the current NDS expression. This expression is the same form as the current NDS expression, with different exponents for the specific gravity and nail diameter parameters. For a design expression, C would be divided by 5 for a final value of 1,652 lbf/in2.

Wallin and Whiteneck (1982) developed a design procedure to assign withdrawal strengths for pallet nails. This procedure was adopted by ASME (1988) for the design of wood pallets. The fifth percentile delayed withdrawal strengths for common and helically threaded nails are predicted by the following ASME expressions:

$$FWI = 8.7D_s \left[1 + 27.15 \quad (D_s - D_T)\frac{H}{L}\right] \qquad ④$$

$$\text{FWRV} = \frac{38.9 \quad (FWI)G^{2.25}}{M \quad -3}$$

where FWI = fastener withdrawal index; FWRF = fastener withdrawal resistance factor; DS = shank diameter (mm); DT = thread-crest diameter of fastener (mm); H = number of helixes along threaded length; L = thread length along fastener shank (mm); G = specific gravity; and M = moisture content (%) between minimum 12% and maximum 28%.

The value of FWI measures the fastener quality relative to a standard nail-2.84-mm shank diameter, 3.35-mm thread crest diameter, and four helical threads at 60° angle and 0.22 threads/mm of thread. For annularly threaded nail strength predictions, (5) may be used by defining an equivalent helically threaded nail by letting H equal the number of annular threads along the length and dividing by 3. Osborn (1985) indicated that the ASME withdrawal expressions were poorly correlated to actual data and only applicable when the connection is assembled green and allowed to dry. He attributed the poor correlation to limited available data, variation in fastener thread characteristics, and a poor moisture relationship. From new and existing withdrawal data, he developed a new FWRF and moisture relationship for delayed withdrawal strength.

Ehlbeck and Siebert (1988) proposed the following expression, to Eurocode 5, for designing annularly and helically threaded nails with a thread angle not more than 60":

$$W = 36 \text{ x } 10^{-6} p^2 D \qquad ⑥$$

where W = characteristic withdrawal design strength per unit length of nail penetration (N/mm); k = characteristic density of member holding the nail point (kg/mm3); and D = shank diameter of nail (mm).

Smooth shank design provisions are currently used in Eurocode 5. No advantage is given for the use of threaded nails (Elhbeck and Larson 1993). Comparison of (2) to (6) indicates threaded nails have double the strength of smooth shank nails, which illustrates the conservative nature of design codes that use the smooth shank expression to design threaded nails. A similar increase was observed in Rammer and others (2001) data for annularly threaded nails.

In all the fasteners design codes, except the ASME provisions, little advantage is given to the increased holding power of annularly threaded nails due to the lack of thread standardization.

ASTM F1667 (2006) was modified to define the thread characteristics for a post-frame annularly threaded nail. Table 45 was modified to define a post-frame ring shank nail identifier, define the maximum and minimum tolerance for difference between the shank and thread crest diameter, and the maximum and minimum distance between thread crests. This standardize of the thread characteristics results in a opportunity and starts the process to increase the design values for post-frame ring shank nails manufactured to this standard.

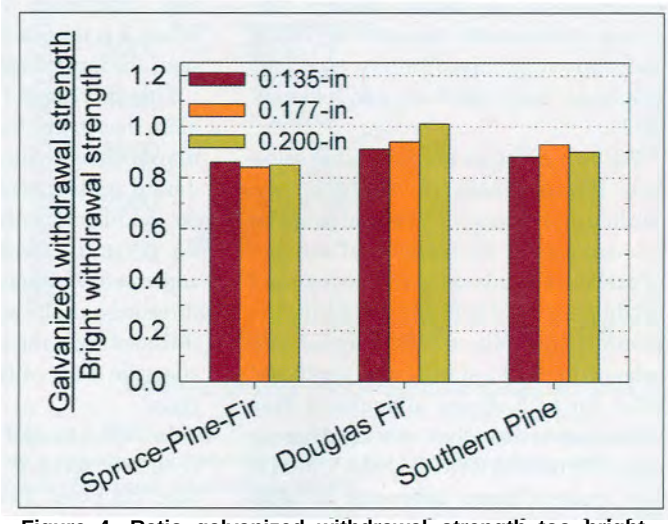

Figure 4. Ratio galvanized withdrawal strength too bright withdrawal strength for shank diameter and wood species.

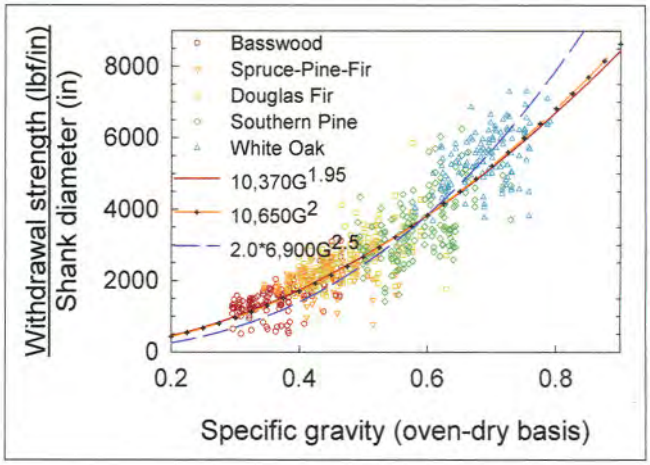

Figure 5. Withdrawal strength divided by shank diameter as a function of specific gravity for bright annularly threaded nails.

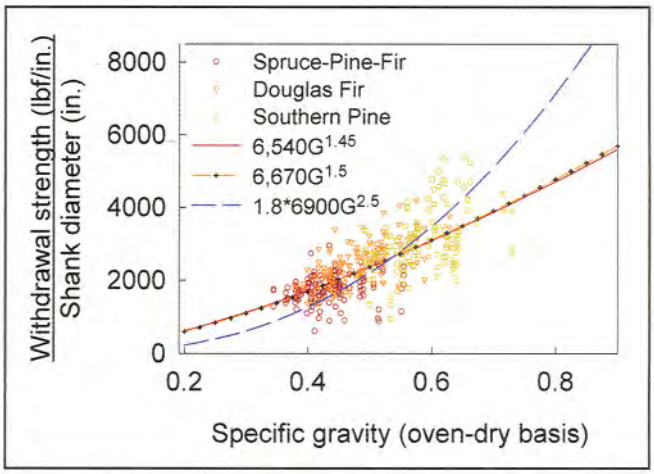

Figure 6. Withdrawal strength divided by shank diameter as a function of specific gravity for galvanized annularly threaded nails.

Experimental Procedure

Withdrawal tests conforming the ASTM D1761 (2005) specifications were conducted on ASTM F1667 post-frame ring shank nails in various wood species. Based on past work, the two most significant parameters for withdrawal strength are nails diameter and the specific gravity of the wood to which the fastener is driven. To investigate nail diameters effects, three shank diameters (0.135, 0.177, and 0.200-in.) were tested for each wood type. The specific type ASTM F1667 post-frame ring shank nail used is this study and nominal dimensions are listed in Table 1.

To capture the specific gravity effects, five different wood species within the bounds of the National Design Specification (0.31 - 0.76) were tested. These woods were Basswood, Spruce-Pine-Fir, Douglas-fir, Southern Pine and White Oak. These five wood species are spaced to span the current range of the National Design Specifications (AF&PA 2005) while focusing on construction related species. All lumber was conditioned at 20°C and 65% relative humidity to achieve an equilibrium moisture content of approximately 12% MC prior to withdrawal testing.

In the original withdrawal strength research (Gahagan and Scholten 1938), on both smooth and cement coated nails, sample replicates of 100 or more were used to investigate unknown trends. Since sufficient information on the key withdrawal parameters are known and the current designs expressions are based on mean value performance, smaller sample size were utilized. From Rammer and others (2001) and Skulteti and others (1997) the standard deviation for similar size annularly threaded nails was roughly 80lb/in2. To obtain an estimated mean within 15 lb/in2 of the mean at a 90% level of confidence at minimum of 43 nails must be tested. For this proposed testing, 50 wood replicates were originally target to determine the withdrawal strength capacity, but due to wood splitting and fastener damage due to hand driving slightly smaller sample sizes resulted (Table 2).

In outdoor applications, hot dipped galvanized fasteners are typically used. Since the hot-dipped process fills in the threads, an assessment of the effect of galvanizing on withdrawal capacity of annular nails is required. It seems unwarranted to duplicate the full test matrix when the galvanizing only affects the fastener characteristics. To investigate the effect of galvanizing, additional tests were performed using the three fastener diameters in Spruce-Pine-Fir, Southern Pine and Douglas fir wood.

All fasteners were cleaned in a three-step process. The fasteners were first placed in an ultrasonic cleaner with a soap solution for 5 min. The fasteners were then rinsed under flowing distilled water before being placed in a distilled water bath that was ultrasonically agitated for 5 min. The fasteners were degreased by rinsing with acetone.

After cleaning, fastener characteristics were both mechanically and optically determined. Mechanical nail measurements (length, shank diameter, crest diameter) were taken with electronic calipers to the nearest 0.0254 mm. Futhermore, a photographic record of all tested nails was preformed using a calibrated optical system.

Lumber specimens were generated from different source boards so that no two nails of a given diameter and type were driven into the same source board. Each nail was driven into the lumber to a depth equal to the thread length. To facilitate insertion in the Southern Pine and White Oak pilot holes were used. Pilot hole diameters conformed to NDS specifications and were 65% of the nail shank diameter.

Each lumber specimen was used to test all the fasteners for a given cell, similar to what was done in original smooth shank withdrawal research (Gahagan and Scholten 1938). This resulted in of 3 bright fasteners driven into the Basswood and White Oak wood, while 3 bright and 3 galvanized fasteners were driven into the Spruce-Pine-Fir, Douglas Fir, and Southern Pine. Each nail was spaced a minimum of 1-3/4-in. from the next nail.

To minimize fiber relaxation effects, specimens were fabricated and tested within 1 h but no sooner than 10 min after fabrication. Withdrawal testing was done in accordance with ASTM D 1761 (1999a) with a minimum test time exceeding 1 min. The fastener head was allowed to rotate during testing. For each test, load versus head movement was recorded and tests were concluded when the load was 30% below the observed maximum.

Finally, oven dry specific gravity and moisture content measurements were determined according to ASTM D2395 and ASTM D4442 using pieces cut from the end of the withdrawal specimen.

Results and Discussion

Average withdrawal strength and coefficients of variation for the bright and galvanized post-frame ring shank nails are listed in Table 2. In general, the immediate withdrawal strength

for bright nails increased with increasing fastener shank diameter and specific gravity. For the Basswood there was a decrease in withdrawal strength for 0.200-in diameter nail and a high coefficient of variation. The COV values for the bright nails ranged between 12.5% and 39.5% with most COV's values in the 20% to 30% range. Similarly, the galvanized nail COV's ranged between 18-29%. This observed variation of strengths was seen in past annularly threaded nail withdrawal studies (Skulteti and others 1997, Rammer and others 2001)

Effect of Diameter

Past withdrawal strength expressions, Eqn 2 and Eqn 6, indicate that withdrawal strength varies linearly with nail diameter (Gahagan and Scholten 1938, Ehlbeck and Siebert 1988). To visually observe the effect of nail diameter on immediate withdrawal strength, the ratio withdrawal strength at any diameter to the withdrawal strength for a 0.135-in diameter nail was plotted versus shank diameter for both bright and galvanized nails. (Figure 3). The relationship between withdrawal strength and fastener diameter is relatively linear, except for the largest diameter bright and galvanized fasteners in Basswood. It is reasoned that the larger diameter fastener caused localized damage to the 1-1/2-in wide wood specimen. The bright fastener ratio of the Southern Pine and White Oak trend higher than results in the Spruce Pine Fir and Douglas Fir. This difference was attributed to less damage of the wood near the fastener due the use of a pilot hole for driving the fastener in Southern Pine and White Oak. Visually the in general relationship between the fastener diameter and withdrawal strength is linear.

Effects of Galvanizing

Past studies indicate that the hot-dripped galvanizing process decreases threaded nail withdrawal capacity. Rammer et al. (2001) found that mean withdrawal strength for galvanized helical nails Southern Pine and Spruce-Pine-Fir was at least 18% lower than that of similar bright threaded nails, while Skulteti et al. (1997) found that withdrawal strength of galvanized nails was 8% lower than that of matched common nails.

Table 1- Nominal Dimensions of Nail Tested

Nail Type	Shank Diameter (in)	Root Diameter (in)	Mzx Crest Diameter (in)	Length (in)
F1667 NL PF-01 B	0.135	0.128	0.145	3.0
F1667 NL PF-09 B	0.177	0.169	0.187	4.0
F1667 NL PF-17 B	0.200	0.193	0.200	5.0
F1667 NL PF-01 G	0.135	0.128	0.145	3.0
F1667 NL PF-09 G	0.177	0.169	0.187	4.0
F1667 NL PF-17 G	0.200	0.193	0.210	5.0

[1]Hot-Dipped Galvanized

Table 2- Test Matrix

		Wood Species and NDS Specific Griavity				
Nail Type	Surface Condition	Basswood (0.32)	Sprice-Pine-Fir (0.42)	Douglas fir (0.49)	Southern Pine (0.55)	White Oak (0.73)
0.135	Bright	49	48	49	49	46
0.177	Bright	49	49	49	50	46
0.207	Bright	49	50	48	50	50
0.135	HD Galv.[1]	–	48	49	48	–
0.177	HD Galv.[1]	–	49	48	49	–
0.207	HD Galv.[1]	–	45	44	48	–

[1]Hot-Dipped Galvanized

In this study, each individual wood specimen contained both a bright and galvanized nail for each nail diameter. To determine if galvanizing had a statistically significant effect, a paired two-sample mean t-test analysis for 9 matched data sets was performed. Eight of the 9 matched sets indicated that a decrease in mean withdrawal strength for galvanized fasteners at a 0.05 level of significance. Only the 0.200-in diameter fastener, driven in Douglas Fir, showed no statistical significant effect to galvanizing. Figure 4 show the ratio of galvanized withdrawal strength to bright withdrawal strength for each fastener shank diameter and wood species tested. The average ratio all fastener diameter in Spruce-Pine-Fir was 0.85, in Douglas Fir was 0.95, and in Southern Pine was 0.90. Southern Pine and Spruce-Pine-Fir ratio are approximately equal to previous studies (Skulteti and others 1997, Rammer and others 2001).

Comparison to Current Design Values

When the original design expression for withdrawal strength was established, the average withdrawal expression was divided by a factor of 6 but after the World War II this factor was adjusted to 5. Therefore; average test post-frame ring-shank withdrawal strength values were divided by 5 to compare to current NDS design values. Design values for NDS were calculated using the average oven- dry specific gravity for each wood species tested, instead of the NDS (AF&PA 2005) design specific gravities. Table 3 shows the ratios of the average withdrawal strength divided by five to the NDS design values. Values greater than one indicate that the allowable test values are greater than those allowed by NDS methods.

As seen in Table 3, ratios for bright nails in Basswood ranged between 1.98 to 2.74; in Spruce Pine Fir ratios ranged between 1.91 and 2.51; in Douglas Fir, ratios ranged between 1.96 and 2.54; in Southern Pine, bright nail values ranged between 1.64 and 1.91; in White Oak, ratios ranged between 1.71 and 1.95; finally, an overall average of 2.08 for all five combined wood species.

Galvanized nail ratios in Spruce Pine Fir, ratios ranged between 1.58 and 2.15;

in Douglas Fir, ranged between 1.90 and 2.28; in Southern Pine, ratios ranged between 1.44 and 1.66; finally, an overall average for all the three wood species was 1.82.

In general the ratios in Table 3 indicate that the uses of current NDS design values for F1667 post-frame ring shank nails significantly under estimates the actual capacity. The greatest difference is for small diameter nails in lower specific gravity species; while the least difference is for large diameter nails in high specific gravity species. A similar observation is observed in both bright and galvanized nails.

Based on all these results, the design approach needs modification to address the higher withdrawal capacity of ASTM F1667 post-frame ring shank nails. A simplified approach would be the adjusted of the NDS design expression by a constant ratio in Table 3. For bright fasteners a conservative approach would be the to multiple current NDS design values of 1.64, the lowest ratio observed in Table 3 for bright nails. Similar for galvanized fastener a constant factor of 1.44 would be applied. Another approach could be application of a factor of 2 for bright fasteners and 1.8 for galvanized fastener, roughly the average ratio for each type of fasteners.

Table 3. Withdrawal Strength of Bright and Galvanized Post-Frame Ring Shank Nails

Lumber type	Nominal Shank Dia. (in)	Average Withdrawal Strength (lbf/in.)	COV	Avg. Specific Gravity	Avg. Moisture Content (%)	NDS (lbf/in.)	Ratio of (Avg. Withdrawal/5) to NDS
Bright (Ungalvanized)							
Basswood	0.135	233	26.7	0.37	10.5	17	2.74
	0.177	281	26.6	0.37	10.5	22	2.55
	0.200	257	39.5	0.37	10.5	26	1.98
SPF	0.135	326	16.6	0.44	13.3	26	2.51
	0.177	373	16.0	0.44	13.3	34	2.20
	0.200	381	21.7	0.44	13.3	40	1.91
Douglas fir	0.135	412	26.6	0.48	12.3	33	2.54
	0.177	451	20.0	0.48	12.3	43	2.12
	0.200	484	22.6	0.48	12.3	50	1.96
SouthernPine	0.135	525	27.7	0.59	10.5	55	1.91
	0.177	592	23.9	0.59	10.5	71	1.67
	0.200	688	24.6	0.59	10.5	84	1.64
White Oak	0.135	791	13.3	0.69	9.5	81	1.95
	0.177	928	15.3	0.69	9.5	105	1.77
	0.200	1049	12.5	0.69	9.5	123	1.71
Galvanized							
SPF	0.135	279	18.8	0.44	13.3	26	2.15
	0.177	313	22.6	0.44	13.3	34	1.84
	0.200	317	23.7	0.44	13.3	40	1.58
Douglas fir	0.135	370	24.3	0.48	12.3	33	2.28
	0.177	421	23.0	0.48	12.3	43	1.98
	0.200	471	18.4	0.48	12.3	50	1.90
SYP	0.135	457	28.7	0.59	10.5	55	1.66
	0.177	542	24.6	0.59	10.5	71	1.53
	0.200	604	23.6	0.59	10.5	84	1.44

Withdrawal Strength Relationship

Historically design withdrawal strength expressions are expressed as a function of specific gravity and fastener diameter. The typical withdrawal strength expression has the following form:

$$W=AG^{b}D^{c} \quad (7)$$

where G is the specific gravity on an oven-dry basis and D is the shank diameter; whereas, A, b, and c are fitting parameters.

A nonlinear regression was preformed with variants of the above expression for both bright and galvanized post-frame ring shank nails. For development of the bright post-frame ring shank nail expression 717 data points were used in the analysis while only 424 data points were using for development of the galvanized relationship. In McLain's (1997) reanalysis of the smooth shank withdrawal strength design expression only 1,914 data points were used. The coefficient of determination, mean percentage deviation (MPD), percentage square error (PSEE), and absolute mean deviation were all determined to access how well the expressions model the relationship of withdrawal strength to specific gravity and shank diameter. Table 4, equations A through C summarizes the results of the nonlinear regression analysis.

Based on all the model fitting statistics, equation A - Table 4 best fits the bright post-frame ring shank data is

$$5{,}360D^{0.62}G^{1.94} \quad (7)$$

and the equation F - Table 4 best fits the galvanized bright post-frame ring shank data is

$$3{,}320D^{0.61}G^{1.47} \quad (8)$$

while the remaining expression represent model variations and fit using the modified NDS design approach.

In both best fit equations [(7) and (8)], the withdrawal capacity is not a linear function of diameter. A similar observation was seen by McLain (1997) for smooth shank nail, although there is a weaker relationship for the post-frame ring shank fasteners. Table 4 shows that using a linear diameter relationship did not significantly change the model statistics. Also since ASTM F1667 limits the shank diameter range for post-frame ring shank nails, a linear relationship for shank diameter in advocated.

To compare the effect linearization, the percent change equation between equations A and B for bright and equations F and G for galvanized fasteners in Table 4 were determined. For the bright fasteners, linearization causes under prediction by 9.6% for 0.135-in diameters and an over prediction of 6.3% for 0.207-in. diameters; similarly for galvanized fasteners, linearization causes under prediction by 9.8% for 0.135-in diameters and an over prediction of 6.6% for 0.207-in. diameters.

Finally simplifying the best fit expression will lead to the following two expressions that predict the ASTM F1667 post-frame ring shank nail withdrawal capacity for bright fasteners:

$$W=10{,}650DG^{2} \quad (9)$$

(and hot-dipped galvanized fasteners:

$$W=6{,}670DG^{1.5} \quad (10)$$

Figure 5 shows withdrawal strength of bright nails divided by shank diameter as a function of specific gravity, linear diameter withdrawal strength expressions (Table 4 - Eqns. B and C), and the 2 times the smooth shank withdrawal. Figure 5 clearly indicates that equation 9 fits the data over the entire specific gravity region. The adjusted smooth shank withdrawal expression tends to under predict the lower specific gravity woods and over predict on the higher side, which is evident in Table 4 statistics.

Figure 6 shows withdrawal strength of galvanized nails divided by shank diameter as a function of specific gravity, linear diameter withdrawal strength expressions (Table 4 - Eqns. G and H), and the 1,8 times the smooth shank withdrawal. Figure 6 clearly indicates that equation 10 fits the data over the entire specific gravity region. The adjusted smooth shank withdrawal expression tends to under predict the lower specific gravity woods and over predict on the higher side, which is evident in Table 4 statistics. Finally, it is evident that the ring-shank nails independent of surface treatment result in experimental withdrawal strength values significantly higher that smooth shank nails.

Table 4. Comparative performance of equations from nonlinear least squares regression of withdrawal data.

Regression Equation	Eqn. No.	r^2	Mean Percentage Difference	Percentage Square Error	Range of Mean Difference	Mean absolute deviation
Bright						
	A	0.84	1.2	19.8	-71 to 58	15.5
	B	0.83	3.3	21.7	-73 to 76	17.0
	C	0.83	4.5	22.4	-73 to 78	17.7
	D[1]	0.60	16.8	32.0	-68 to 102	25.1
	E[2]	0.78	15.9	35.2	-70 to 128	27.1
Galvanized						
	F	0.58	0.02	21.1	-67 to 72	16.3
	G	0.55	1.9	22.7	-66 to 81	17.3
	H	0.54	2.2	22.7	-66 to 83	17.3
	I	0.48	7.7	26.6	-63 to 109	20.9
	J[2]	0.30	12.1	33.3	-64 to 135	26.1

[1]Expression developed by Rammer and others (2001)

[2]Modified approach using historical smooth, shank nail expression (Gahagan and Scholten 1938)

Conclusions

ASTM F1667 post-frame ring shank nails were tested to determine withdrawal strength in five wood species that span the specific gravity range of construction lumber. Additional parameters considered were fastener surface condition, in three wood species, and fastener diameter, in all wood species. Based on matched comparisons of hot-dipping galvanizing does decrease the withdrawal strength capacity but, at most, the decrease was 20%.

Current NDS design procedure for withdrawal strength of threaded nails underestimates the performance of both galvanized and bright nails. Based on this study, design withdrawal values for bright nails were under estimated by 40% to 60% and, for hot-dipped galvanized by 31% to 54%. The greater difference was observed for smaller diameter and lower specific gravity wood. Several empirical non-linear models were developed and evaluated to related withdrawal strength capacity to specific gravity and fastener diameter. Two simpler models were advocated for using determining the withdrawal capacity of F1667 post-frame ring shank nails. ■

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