WITHDRAWAL STRENGTH OF THREADED NAILS

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ABSTRACT: Threaded nails are used in wood construction because of their superior performance, but relatively few tests have been conducted on nails larger than 12d (3.76 mm diameter). Experience has suggested that threaded nail withdrawal design values are too conservative. The Forest Products Laboratory and Washington State University have been cooperatively characterizing the strength of threaded nails over a range of wood species and nail types. This paper focuses on the immediate withdrawal strength of annularly threaded nails in Douglas Fir and Spruce-Pine-Fir, helically threaded nails in Southern Pine, and smooth nails in Southern Pine and Spruce-Pine-Fir lumber. Average withdrawal strength of threaded nails was greater than that of smooth shank nails of the same diameter. In comparison of experimental withdrawal strength to existing design procedures for assigning allowable withdrawal strength design values, annular shank nails showed the greatest difference. Withdrawal strengths of nails from five different manufacturers were not significantly different. Comparisons of the effect of galvanizing on withdrawal strength were inconclusive.

INTRODUCTION

Threaded nails, initially used in shoe, automobile, and boat industries (Stem 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 postframe 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.

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 (Fig. 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).

For threaded nails, the National Design Specification (NDS) for Wood Construction specifies that shank steel have a high carbon content and be heat treated and tempered to achieve higher yield strength values than that of comparable common nail steel [American Forest and Paper Association (AFPA) 1997]. To inhibit rust development in damp environments, 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.

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 fitiers surrounding the nail relax, causing withdrawal strength to decrease. 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 7*d* common nails 105 days after the nails were driven into matched specimens. Threaded nails resist withdrawal forces by friction and by wood fibers lodged between the threads. When threaded nails are driven into wood, the wood fibers separate and lodge between the read 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) showed an increase in withdrawal strength of threaded nails driven into green lumber as the lumber dried. Furthermore, galvanized coatings may change withdrawal strength by filling and smoothing thread valleys, especially in annular nails (Feldborg and Johansen 1972).

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). Stem later investigated the use of small-sized

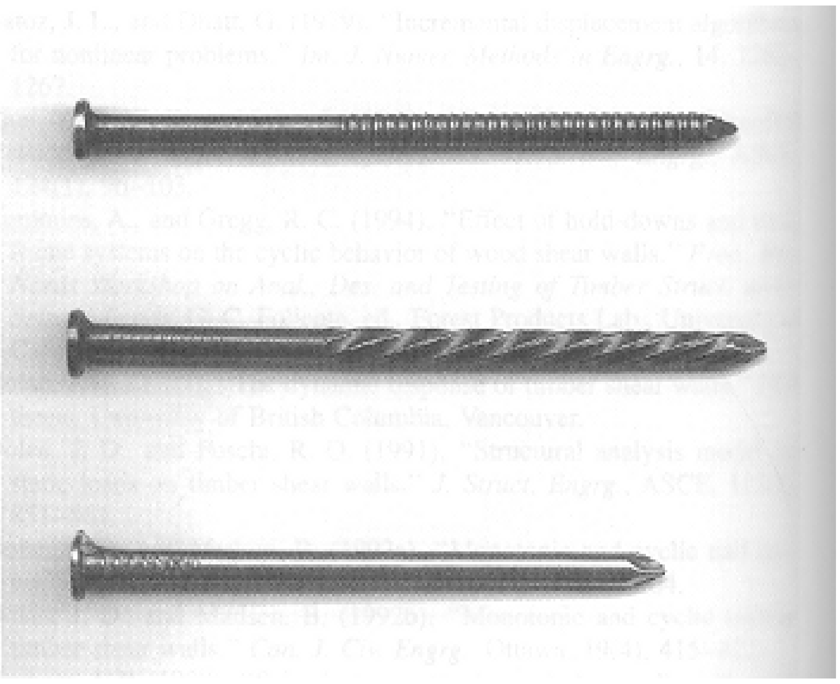

FIG. 1. Nail Classification (Top to bottom): Annularly Threaded, Helically Threaded, Smooth

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Previous studies on threaded nails were limited and focused on fundamental mechanics and moisture effects. 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. Past withdrawal testing used small replicate numbers and cannot be used to determine the underlying probabilistic distributions.

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 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 NDS 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.

The goal of the cooperative study reported here was to gain understanding of threaded nails in withdrawal and lateral loading. This report addresses only the withdrawal performance of threaded nails with respect to common nails. Primary areas of investigation were: (1) withdrawal strength of threaded nails manufactured by different producers; (2) effects of galvanizing on withdrawal strength of helically threaded nails; (3) probability distribution of withdrawal strength data; and (4) comparison of immediate withdrawal strength predictions with actual data.

WITHDRAWAL RELATIONSHIPS AND DESIGN PROVISONS

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 1997) are based on research using bright, common degreased smooth shank nails. Based on this research, the following expression was developed to relate withdrawal strength, specific gravity, and nail diameter:

$$W = KG^{5/2}D \tag{1}$$

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); and K = constant factor, accounting for safety, experience, and duration of load (9.515 N/mm^2).

Eq. (1) 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). This expression 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. (1) 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 20*d* to 60*d*, whereas the threaded nail diameter remains constant at 4.50 mm in the 20d–60d range (*Commentary* 1993).

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

$$W = CG^{2.24}D^{0.84} \tag{2}$$

where C = empirical constant that equals 57 and a percent standard error 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 11.4.

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:

$$FWI = 8.7D_s\left[1 + 27.15(D_T - D_S)\frac{H}{L}\right] \tag{3a}$$

$$FWRF = \frac{38.9(FWI)G^{2.25}}{(M - 3)} \tag{3b}$$

where FWI = fastener withdrawal index; $FWRF$ = fastener withdrawal resistance factor; D_S = shank diameter (mm); D_T = 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, (3) 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°:

$$W = 36(10\text{-}6)\rho_k^2 D \tag{4}$$

where W = characteristic withdrawal design strength per unit length of nail penetration (N/mm); ρ_k = characteristic density of member holding the nail point (kg/mm^3); 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 (1) to (4) 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.

TESTING PROCEDURES

Three classifications of nails were tested for withdrawal strength: annularly threaded, helically threaded, and smooth

Lumber type[a] (1)	Tests (number) (2)	Shank diameter (mm) (3)	Thread-crest diameter[b] (mm) (4)	Thread-root diameter[b] (mm) (5)	Shank diameter[b] (mm) (6)	Nail source (7)	FWI (8)
SPF	10	2.52	2.74	2.53	2.55	A	48.8
	10	3.43	3.66	3.27	3.45	B	65.0
	50	3.76	4.04	3.60	3.82	C	66.5
	10	4.50	4.66	4.41	4.59	C	54.7
	10	4.50	4.74	4.34	4.56	B	77.5
	10	5.26	5.35	4.92	5.12	B	102.2
D. Fir	10	2.52	2.75	2.55	2.54	A	51.5
	9	2.87	3.17	2.88	2.95	A	63.7
	10	3.05	3.41	2.96	3.19	B	69.8
	10	3.43	3.68	3.32	3.46	B	65.1
	9	3.68	3.77	3.66	3.67	D	66.5
	10	3.76	3.97	3.61	3.81	B	61.1
	10	3.76	4.01	3.73	3.91	C	51.4
	10	4.50	4.73	4.41	4.57	C	73.6
	10	4.50	4.75	4.35	4.58	B	77.4
	10	5.26	5.38	4.94	5.12	B	110.1
SPF	10	2.52	2.63	—	2.53	A	38.6
	10	2.87	3.07	—	2.90	A	40.9
	10	3.05	3.28	—	3.13	A	39.6
	10	3.43	3.70	—	3.46	A	47.3
	10	3.43	3.64	—	3.45	B	51.7
	10[c]	3.43	3.73	—	3.60	B	46.7
	50	3.76	3.96	—	3.78	B	54.0
	10	4.50	4.80	—	4.53	B	78.9
S. Pine	10	2.52	2.62	—	2.53	A	38.6
	10	3.43	3.63	—	3.45	B	54.1
	50	4.50	4.69	—	4.54	B	62.0
	10[c]	4.50	4.80	—	4.72	B	53.6
(c) Smooth Shank							
SPF	10	3.33	—	—	3.37	FPL	29.3
	50	4.11	—	—	4.11	FPL	35.8
	10	6.68	—	—	6.65	E	57.9
S. Pine	10	3.33	—	—	3.37	FPL	29.3
	10	3.76	—	—	3.73	FPL	32.5
	50	4.11	—	—	4.11	FPL	35.8
	10	6.68	—	—	6.66	E	57.9

shank (common) (Fig. 1). Annularly threaded nails were obtained from four manufacturers (A, B, C, D), helically threaded nails from two manufacturers (A, B), and smooth nails from one manufacturer (E) and Forest Products Laboratory (FPL) stock nails. Ten nails were tested for each combination of type, material, and diameter considered, except five groups of 50 nails were tested to classify the underlying statistical distribution for withdrawal strength (Table 1). Nails that were not straight, had poorly defined threads, or did not represent the type of nail designated on the box label were culled. This procedure typically excluded two or three nails from each box. Because nails were culled, some level of nail standardization is required before threaded nail design values are codified.

Nail shank diameters for the entire test matrix ranged between 2.52 and 6.68 mm (Table 1). Two helically threaded nail replicates, one driven into Spruce-Pine-Fir and the other driven into Southern Pine, had a galvanized coating to provide insight about the effect of galvanizing on withdrawal strength. Prior to testing, all nails were degreased in a trichloroethane 1-1-1 bath for a minimum of 20 min and then air dried for a minimum of 1 h before being driven into the wood. Nails were degreased to reduce variability of withdrawal strength and allow better characterization of thread geometry on strength. Before driving the nails into the wood, the shank diameter, thread-crest diameter, thread-root diameter, and nail length were measured (Table 1). Nail measurements were taken with electronic calipers to the nearest 0.0254 mm. Only the crest diameter is reported for helically threaded nails because it was impossible to position the calipers to obtain a consistent thread-root diameter measurement.

To evaluate specific gravity effects on withdrawal strength, nails were driven into three different lumber species groups: Spruce-Pine-Fir, Douglas Fir, and Southern Pine. All lumber was conditioned at 20°C and 80% relative humidity for several months to achieve an equilibrium moisture content of approximately 12%. 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 of 70% of the nail length or thread length, whichever was shorter. No predrilled pilot holes were used to guide the nails, but care was taken so that the nails were not driven near or into knots, wane, or checks. 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 1761-88 (1999a) with a minimum test time exceeding 1 min. The fastener head was allowed to rotate during with-

Lumber type (1)	Nominal shank diameter (mm) (2)	Tests (number) (3)	Withdraw strength[a] (N/mm) (4)	COV (%) (5)	MC[a] (%) (6)	Dry SG[a] (7)	Nail source (8)	NDS (N/mm) (9)	Average15 to NDS ratio (10)
				(a) Annularly Threaded Nails					
SPF	2.52	10	33.31	32.4	13.6	0.39	A	2.98	2.23
	3.43	10	32.02	30.8	13.6	0.39	B	3.33	1.92
	3.76	50	46.66	22.4	14.0	0.39	C	3.68	2.54
	4.50	10	54.67	13.8	13.6	0.40	C	4.73	2.31
	4.50	10	49.87	25.7	13.6	0.40	B	4.73	2.11
	5.26	10	59.66	13.6	13.9	0.39	B	5.08	2.34
D. Fir	2.52	10	54.74	29.0	13.1	0.52	A	6.30	1.74
	2.87	10	59.01	23.4	13.1	0.52	A	6.30	1.87
	3.05	10	72.92	21.8	13.3	0.51	B	5.95	2.45
	3.43	10	50.85	32.4	13.3	0.51	B	6.65	1.53
	3.68	10	54.99	17.2	13.2	0.51	D	7.36	1.49
	3.76	10	60.56	26.2	13.2	0.51	B	7.36	1.64
	3.76	10	69.08	24.3	13.2	0.50	C	7.01	1.97
	4.50	10	77.03	17.7	13.2	0.50	C	8.23	1.87
	4.50	10	69.97	21.2	13.1	0.50	B	8.23	1.70
	5.26	10	90.70	17.0	13.1	0.50	B	9.63	1.88
				(b) Helically Threaded Nails					
SPF	2.52	10	19.58	30.6	13.9	0.39	A	2.98	1.31
	2.87	10	23.75	17.5	14.0	0.39	A	2.98	1.59
	3.05	10	28.79	26.0	14.0	0.39	A	2.98	1.93
	3.43	10	26.68	25.7	14.0	0.39	A	3.33	1.60
	3.43	10	28.52	40.9	14.0	0.37	B	2.98	1.91
	3.43[b]	10	23.52	39.0	14.1	0.40	B	3.68	1.28
	3.76	50	33.42	27.5	14.0	0.39	B	3.68	1.81
	4.50	10	37.26	36.4	14.1	0.40	B	4.73	1.58
S. Pine	2.52	10	37.27	12.3	11.3	0.59	A	8.47	0.88
	3.43	10	49.19	18.4	11.3	0.59	B	9.56	1.03
	4.50	50	70.35	21.1	11.1	0.58	B	11.89	1.18
	4.50'	10	52.06	28.4	11.0	0.57	B	10.33	0.91
SPF	3.33	10	24.24	32.8	13.9	0.41	FPL	3.33	1.46
	4.11	50	25.35	31.2	14.0	0.39	FPL	3.67	1.38
	6.68	10	31.04	32.8	13.9	0.41	E	6.83	0.82
S. Pine	3.33	10	35.61	48.3	11.0	0.55	FPL	7.18	0.99
	3.76	10	34.45	38.6	11.0	0.55	FPL	8.06	0.85
	4.11	50	32.70	21.6	11.1	0.58	FPL	9.98	0.66
	6.68	10	39.27	35.6	11.0	0.57	E	15.59	0.50

Note: MC = moisture content, SG = specific gravity, SPF = Spruce-Pine-Fir, D. Fir = Douglas Fir, and S. Pine = Southern Pine.
[a]Average values.
[b]Double-hot-dipped galvanized nails.

drawal. Oven-dry volume specific gravity and moisture content were determined on each specimen according to Method A of ASTM D 2395-93 (1999b) and ASTM D4442-92 (1999c).

RESULTS AND DISCUSSION

Average withdrawal strengths and coefficients of variation (COVs) for the annularly threaded, helically threaded, and smooth nails are listed in Table 2. Withdrawal strength generally increased with nail diameter and specific gravity for each type of nail tested. The COV values indicate that the annularly threaded nails were the least variable (17–32%), followed by helically threaded nails (12–41%), and the smooth nails showed the greatest variability (22–48%).

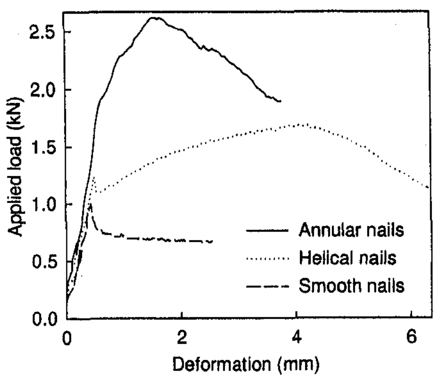

FIG. 2. Load-Deformation Curves for Nails of Similar Size, Specific Gravity, and Moisture Content

Withdrawal Performance

Representative load-displacement curves for annularly and helically threaded nails of equal diameter fabricated by manufacturer B and smooth nails in Spruce-Pine-Fir with similar specific gravity and moisture content are shown in Fig. 2. For annularly threaded nails, the curve shows a linear region that gradually becomes nonlinear as it approaches the maximum load. After the maximum, the load decreased steadily until testing was terminated. Helically threaded nails showed a strong linear relationship between load and displacement until a sudden drop or flattening in the curve, after which there was a slower rate of increase in the load until maximum as the helically threaded nail slowly backed out in a rotating manner. Smooth shank nails showed a linear relationship between load and displacement until a significant load drop, after which the load reached a plateau. This constant load region represents nail strength resisted by the dynamic coefficient of friction as the nail backs out.

The load-displacement curves for the annularly threaded and common nails are similar to the response reported by Skulteti et al. (1997) and Stern (1950b) for ring-shank and common nails in Southern Pine. Of the two types of threaded nails, annular nails had greater strength values but lost strength after the first maximum, whereas helically threaded nails had lower initial strength but increased strength after an initial load drop.

An analysis of variance (ANOVA) was performed on the log of withdrawal data from tests of smooth, helically threaded, and annularly threaded nails of similar diameter to identify whether strength values were significantly different. ANOVA calculations were performed using a general linear model and Tukey's Studentized range test for multiple hypothesis comparison at a 0.05 level of confidence (*SAS/STAT* 1988). Comparisons of the 3.33-mm smooth and 3.43-mm helically and annularly threaded nails in Spruce-Pine-Fir revealed no statistically significant difference of median with-

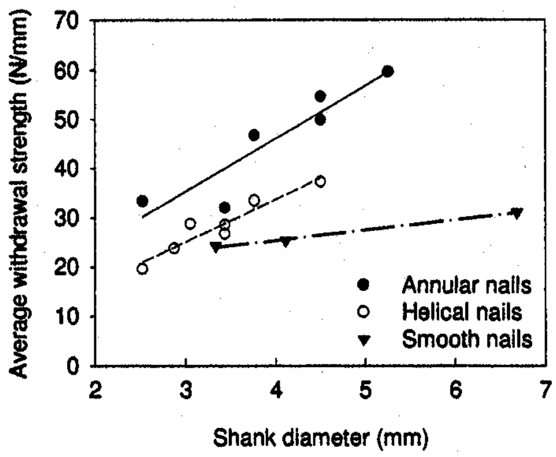

FIG. 3. Average Withdrawal Strength versus Nominal Shank Diameter for Nails Driven into Spruce-Pine-Fir, by Nail Type

drawal strength, although the mean of the annular nails was 32% greater than the mean of common nails. Fig. 3 shows the average withdrawal strength as a function of shank diameter for all nails tested in Spruce-Pine-Fir along with best-fit lines for each nail classification. As this figure shows, annularly threaded nails had the greatest withdrawal strength, followed by helically threaded nails and smooth shank nails. Fig. 3 also indicates that both annularly and helically threaded nails have withdrawal strengths that increase at a faster rate with an increase in shank diameter than do the withdrawal rates of smooth shank nails. In Southem Pine, comparison of 3.33-mm smooth and 3.43-mm helically threaded nails revealed a significant difference in median withdrawal strength; mean strength of helically threaded nails was 38% greater than that of smooth nails.

Effects of Manufacturing and Galvanizing

An ANOVA was performed on the withdrawal strength data for nails of similar type and diameter driven into the same wood species but made by different manufacturers. Based on the ANOVA using the same range test and level of confidence as used for previous comparisons, nail manufacturer source had no effect on the withdrawal capacity of annularly or helically threaded nails.

An ANOVA using the same range test and level of confidence as previous comparisons was performed to determine the effects of galvanizing on the log withdrawal strength of threaded nails. Galvanizing effects on withdrawal strength were not as clear as manufacturer effects. The 3.43-mm-diameter helically threaded nails driven into Spruce-Pine-Fir showed no statistical difference in median withdrawal strength, but mean withdrawal strength was lower for galvanized nails. The 4.50-mm-diameter helically threaded nails driven into Southern Pine showed a statistical difference in median withdrawal strength at a 0.05 level of significance. These comparisons indicate the uncertainty of the effect of galvanizing on

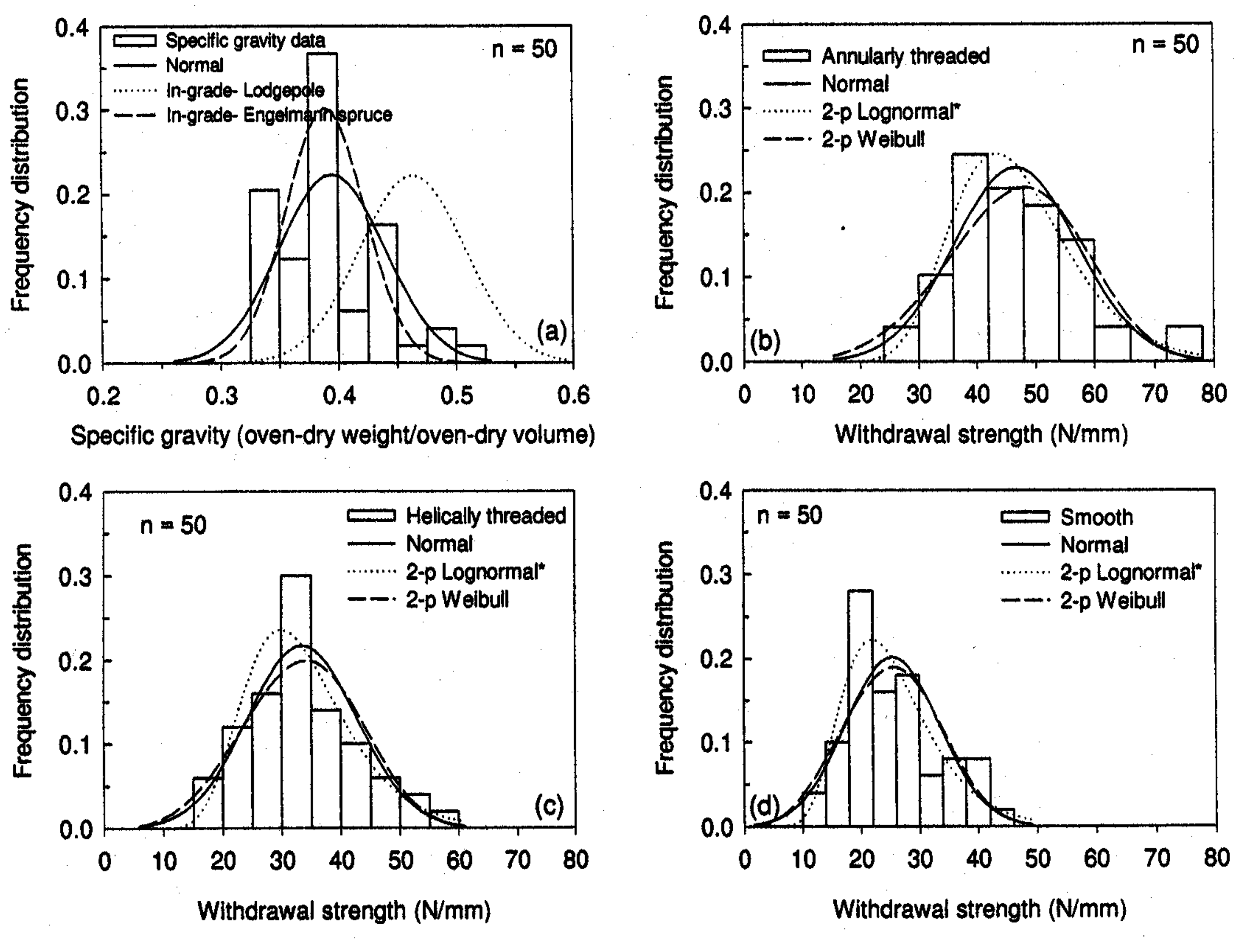

FIG. 4. Histograms for Spruce-Pine-Fir Data: (a) Specific Gravity; (b) Annularly Threaded Nails; *(c)* Helically Threaded Nails; (d) Smooth Nails

helically threaded nails. Nevertheless, caution should be used when assigning withdrawal strengths for coated nails. In both cases, there was a minimum 18% decrease in mean withdrawal strength of galvanized nails as compared to that of ungalvanized nails. Skulteti et al. (1997) found that the average withdrawal strength of galvanized nails was 8% lower than that of matched common nails.

Strength Distributions

For Southern Pine and Spruce-Pine-Fir species groups, 50 replications were made of one nail size in each nail shank classification to determine the best fitting probability distribution, resulting in a total of five sets of 50 replicates. Three probability distributions were examined: normal, lognormal, and two-parameter Weibull. These distributions were chosen because they are typically used to classify mechanical response in wood and wood-based materials. Chi-squared, Anderson-Darling, and K-S tests were performed to evaluate the goodness of fit of the distributions. All distributions fit the data well, but the lognormal distribution was the best fit for four of the five groups. Figs. 4 and 5 show all the distributions superimposed on the withdrawal strength histograms. Table 3 lists the best-fit distribution and distribution parameters for each set of 50 nail types tested. Skulteti et al. (1997) found that the Weibull and lognormal distributions fit withdrawal strength distributions of ring-shank nails in Southern Pine.

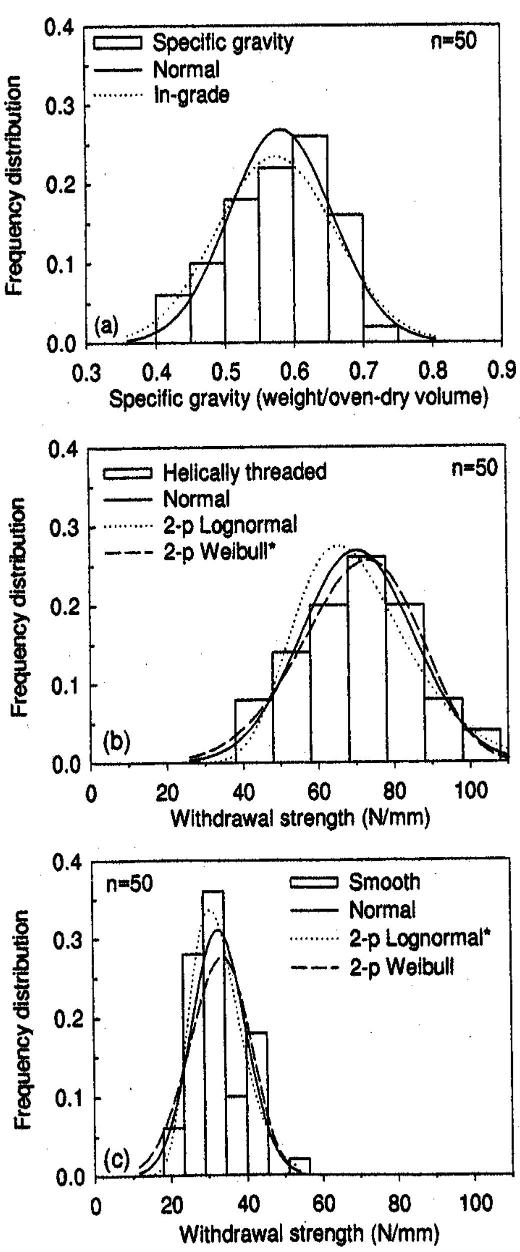

FIG. 5. Histograms for Southern Pine Data: (a) Specific Gravity; (b) Helically Threaded Nails; (c) Smooth Nails

TABLE 3. Distribution Parameters for Ultimate Withdrawal Strength

Lumber type (1)	Nail type (2)	Nominal shank diameter (mm) (3)	Best-fit distribution (4)	Parameters[a] Scale	Shape
SPF	Annularly threaded	3.76	Lognormal		
SPF	Helically threaded	3.76	Lognormal	3.47	0.272
S. Pine	Helically threaded	4.50	Weibull		
SPF	Smooth shank	4.11	Lognormal	3.18	0.312
S. Pine	Smooth shank	4.11	Lognormal	3.47	0.208

Note: SPF = Spruce-Pine-Fir and S. Pine = Southern Pine.
[a] For lognormal, scale designates mean of $\ln(x_i)$ and shape.

Comparisons to Current Design Values

All average withdrawal strength data were divided by 5 to compare to current NDS design values. Design values using NDS procedures were not calculated using the specific gravity values published in Table 12A of NDS-97 (AFPA 1997). Instead, average tested *dry* specific gravity values for Douglas Fir, Southern Pine, and Spruce-Pine-Fir were used. Table 2 shows the ratios of NDS design values to the withdrawal strength value divided by 5. A value of 1.0 indicates that the allowable test value equals the NDS allowable; values >1.0 indicate allowable test values greater than those allowed by NDS methods. For the annular nails in Spruce-Pine-Fir, the ratio ranged between 1.9 and 2.5, with an average of 2.24; in Douglas Fir, the ratio ranged between 1.5 and 2.5, with an average of 1.81. For the ungalvanized helically threaded nails, the ratio ranged between 1.3 and 1.9, with an average of 1.68, for Spruce-Pine-Fir and between 0.9 and 1.2, with an average of 1.00, for Southern Pine.

For annularly and helically threaded nails, the ratio was similar across all shank diameters for a given wood species. For the low specific gravity wood, Spruce-Pine-Fir, the NDS design procedure values were conservative for both annularly and helically threaded nails. For the high specific gravity wood species (Douglas Fir and Southern Pine), the difference between the NDS design procedures and mean experimental values was lower, and in the case of five helically threaded nails in Southern Pine, the values were nearly equivalent.

Based on these experimental data, the NDS design expression could be modified for annularly and helically threaded nails. Annularly threaded nail withdrawal design values could be raised by 50% to bring them in line with experimental observations. For helically threaded nails, only the low specific gravity (Spruce-Pine-Fir) withdrawal strengths could be increased. Ignoring the 2.52-mm-diameter and galvanized nail data, withdrawal design values for helically threaded nails in Spruce-Pine-Fir could be raised 50% to bring them in line with test observations, but no withdrawal increase is advised for Southern Pine.

Expressions for the mean withdrawal strength of annularly and helically threaded nails were derived using the same format as the current NDS expression [(1)] with all the test data generated. For annularly threaded nails that expression would be

$$W = 42.8G^{1.38}D \qquad (5)$$

where the coefficient of determination $r^2 = 0.57$. For helically threaded nails, the expression would be

$$W = 29.6G^{1.28}D \qquad (6)$$

where $r^2 = 0.76$.

Fig. 6 shows withdrawal strength divided by shank diameter

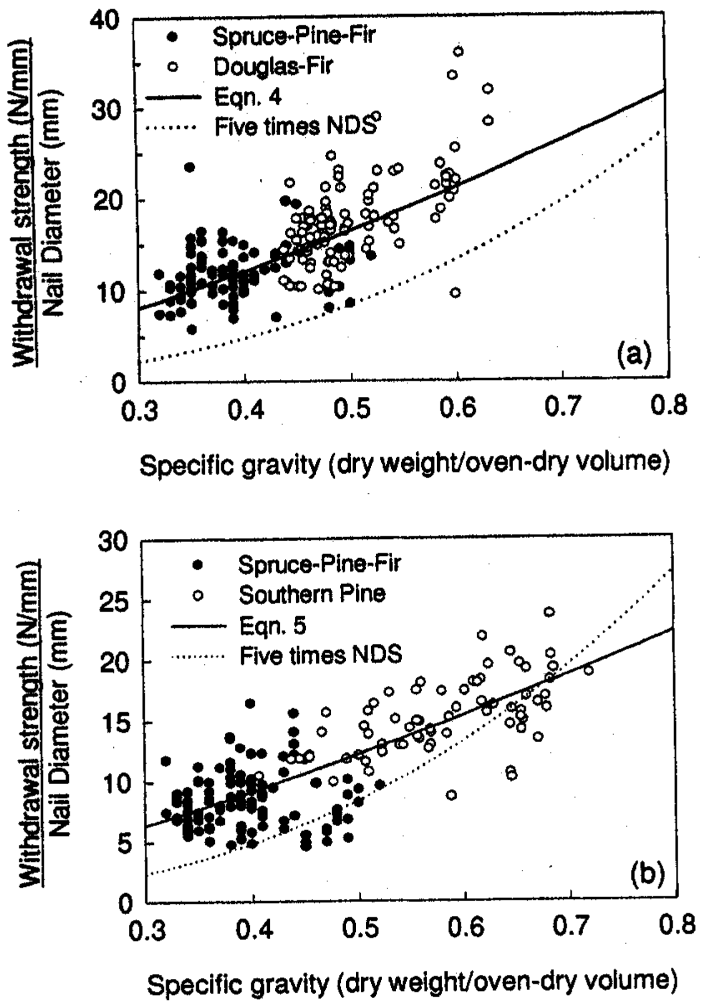

FIG. 6. Withdrawal Strength Divided by Shank Diameter as Function of Specific Gravity for: (a) Annularly Threaded; (b) Helically Threaded Nails

as a function of dry volume specific gravity for annularly and helically threaded nails, the current NDS expression multiplied by the adjustment factors, and Eqs. (5) and (6). For annularly threaded nails, Fig. 6(a) clearly indicates that the current NDS expression underpredicts the mean trend for both tested wood species. For helically threaded nails, however, Fig. 6(b) indicates that the current NDS expression underpredicts the mean trend of the Spruce-Pine-Fir data set. Both expressions show that the dependence on specific gravity is lower for threaded nails as compared to the 5/2 power in (1). This lower dependence of specific gravity might explain the difference in the behavior of the helically threaded nails in Southern Pine, and in general, smaller differences are observed between adjusted average values and NDS design values in higher specific gravity material.

Smooth nails with a shank diameter <4.11 mm exhibited withdrawal strengths similar to the NDS predictions. For these and smaller smooth nails in Spruce-Pine-Fir, the empirical expression consistently overpredicted withdrawal strength, but for Southern Pine material, the expression consistently underpredicted the average. For the spikes (6.68-mm-diameter nails) in Southern Pine and Spruce-Pine-Fir, the NDS predictions are extremely unconservative, especially for spikes in Southern Pine (50% below predicted values). Only two other studies have investigated large diameter nails. Gahagan and Scholten (1938) found similar withdrawal strengths for 10 spikes driven into Southern Pine. Stem (1957) found withdrawal strengths similar to NDS allowable values, although only four specimens were tested. Based on past and present data, current NDS expressions applied to large-diameter smooth nails may be unconservative, especially when these nails are driven into Southern Pine.

The experimentally determined immediate withdrawal results presented in this paper cannot be directly compared to the ASME design procedure (ASME 1988). The advantage of

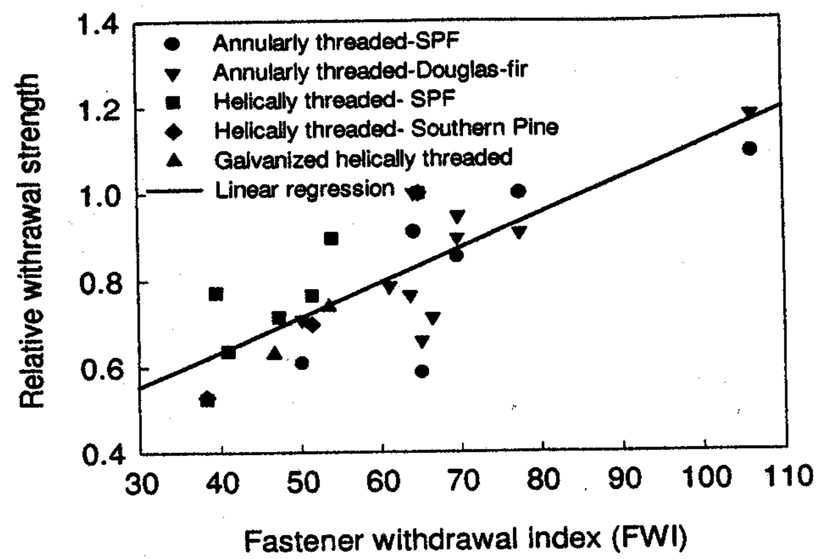

FIG. 7. Normalized Withdrawal Strength as Function of Fastener Withdrawal Index *FWI* for Annularly and Helically Threaded Nails in Spruce-Pine-Fir (SPF), Douglas Fir, and Southern Pine

the ASME procedure is the use of the fastener withdrawal index *FWI* to account for the effect of different thread characteristics on delayed withdrawal strength. For each group of tested nails, the *FWI* was calculated using the average thread characteristics for each type of nail tested. To determine whether *FWI* or a similar type of expression could be used to characterize the immediate withdrawal strength of threaded nails, withdrawal results were normalized at a common *FWI* value. This *FWI* value was about 64 for both the type C,4.50-mm-diameter annular nails and the type B helically threaded nails. Normalization eliminated the effect of specific gravity on withdrawal results. Fig. 7 shows the normalized strength results for all the annularly and helically threaded nails versus *FWI* along with a best-fit line. This figure clearly shows that as *FWI* increases, the relative withdrawal strength of the threaded nail increases; this is also shown by the coefficient of determination of 0.62 for the best-fit line. Even the relative withdrawal strength of the galvanized nails seems to fall within the general trend of the overall data. Therefore, it seems possible to use an expression characterizing the thread geometry, such as *FWI*, to predict the immediate withdrawal of different types of threaded nails. Unfortunately, this limited data set is not adequate to develop this expression.

CONCLUSIONS

Annularly threaded, helically threaded, and common nails were tested to determine withdrawal strengths in Douglas Fir, Southern Pine, and Spruce-Pine-Fir at 12% moisture content. Based on a comparison of helically and annularly threaded nails of approximately the same diameter in Southern Pine, the median withdrawal strengths were significantly different. A similar comparison of Spruce-Pine-Fir concluded no significant difference in mean withdrawal strength for different types of nails.

The source of nails had no effect on withdrawal strength. The comparison investigating the effect of galvanizing on withdrawal strength of helically threaded nails was not conclusive, although mean withdrawal strength was at least 18% lower than that of corresponding mean withdrawal strength of ungalvanized nails. Based on five different groups with 50 replications each, a lognormal distribution is the underlying distribution for withdrawal strength.

Current NDS design procedure for withdrawal strength underestimates the performance of threaded nails. The greatest differences were observed for annularly threaded nails. Helically threaded nails in Spruce-Pine-Fir also exceeded the design estimates. Based on this study, design withdrawal values for annularly threaded nails could be increased by 50% for the full range of specific gravity values examined. Similarly, design withdrawal values for helically threaded nails could be increased by 30% in low specific gravity material such as Spruce-Pine-Fir. Although this study justifies increased withdrawal values for threaded nails, increases should only be allowed after standard thread characteristics are established. Current general nail classifications are not sufficient in defining the critical thread characteristics that influence withdrawal strength, such as thread length, thread-crest diameter, and root diameter. Once standardization is established, it would be possible to predict immediate withdrawal strength based on these thread characteristics through a parameter such as the fastener withdrawal index *FWI*. Finally, this study, when considered with past research, indicates that design expressions for large-diameter smooth nails when driven into Southern Pine may be unconservative, indicating the need for more research on the withdrawal strength of large-diameter smooth shank nails.

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