Withdrawal Strength and Bending Yield Strength of Stainless Steel Nails

Douglas R. Rammer, M.ASCE[1]; and Samuel L. Zelinka[2]

Abstract: It has been well established that stainless steel nails have superior corrosion performance compared to carbon steel or galvanized nails in treated wood; however, their mechanical fastening behavior is unknown. In this paper, the performance of stainless steel nails is examined with respect to two important properties used in wood connection design: withdrawal strength and nail bending yield strength. Different nail diameters, wood specific gravities, and nail manufacturers were examined. The current withdrawal design equations, developed from carbon steel nail data, overpredict the expected withdrawal strength when used for stainless steel nails, reducing the safety factor. As a result, a new equation was developed to predict the nail stainless steel withdrawal capacity. The data further indicate that nail bending yield strength values for stainless steel were similar to carbon steel data. **DOI: 10.1061/(ASCE)ST.1943-541X.0001088.** © *2014 American Society of Civil Engineers.*

Author keywords: Stainless steel; Nail withdrawal; National design specifications for wood construction; Nail bending yield strength; Wood structures.

Introduction

Metal fasteners have been used in wood construction for centuries. For outdoor environments, chemicals are added to wood to increase durability and hence service life. Unfortunately, wood preservatives—especially water-based preservatives—can decrease the service life of the metal fastener by making the fastener environment more corrosive. Stainless steel fasteners traditionally perform well in treated wood and are the fastener of choice from a durability/corrosion perspective, but their connection performance is unknown. For fastener withdrawal design, it is sometimes assumed that stainless steel nailed joints have the same capacity as those nailed with carbon steel or galvanized steel fasteners; however, the withdrawal capacity is a function of the coefficient of friction of the wood and metal. Exploratory testing by Bonser and Scholten, in 1947, comparing the withdrawal strength of steel, aluminum, and copper nails and found that aluminum nails had lower withdrawal strength. The Wood Handbook [Forest Products Laboratory (FPL) 2010] indicates that the surface condition of the nail at the time of driving influences the initial withdrawal resistance, but the discussion of this effect is centered on surface coatings such as cement or polymers, not the metal type. Because it is also well known that the coefficient of friction of stainless steel fasteners is appreciably different from carbon steel fasteners, it seems plausible that stainless steel fasteners might have different withdrawal strengths than carbon steel fasteners (MacKenzie and Karpovich 1968; Andersson et al. 2007).

In contrast to smooth shank nails, which resist withdrawal through frictional forces, threaded nails entangle wood fibers in the threads, and the withdrawal strength is dependent on breaking the wood fibers lodged between the threads. Therefore, greater withdrawal capacity (Rammer et al. 2001; Skulteti et al. 1997; Rammer and Mendez 2008) is expected, and the effect of friction is expected to be less for the withdrawal strength of threaded nails.

For the reasons that stainless steel nails in new wood preservative treatments are increasingly recommended and the coefficient of friction of stainless steel is different than carbon steel, an investigation into the mechanical properties of stainless steel nailed connections is warranted. This study was performed to answer the following questions:

1. How does tested stainless steel withdrawal strength compare to equations used in design codes to predict nail withdrawal strength?
2. Does the withdrawal strength depend on the manufacturer, as different manufacturers may employ different methods for drawing wire and surface treatments on the fasteners, which might affect the friction coefficient?
3. How does the withdrawal strength of threaded stainless steel nails compare to equations used to predict withdrawal strength of threaded nails?
4. How does the stainless steel fastener bending yield strength differ from national design specification (NDS) [American Wood Council (AWC) 2012]—prescribed values for carbon steel nails?

Methods and Materials

Withdrawal Tests

Withdrawal tests conforming to ASTM D1761-88 (ASTM 2009) specifications were conducted to examine (1) the effect of specific gravity and nail diameter on the withdrawal strength of stainless steel nails, (2) the effect of the fastener manufacturer on the withdrawal strength of stainless steel nails, and (3) the withdrawal strength of stainless steel threaded ring shank nails.

Table 1 gives the withdrawal test matrix. For Objective 1, approximately 50 replicates were tested for each combination of three nail diameters and three species groups for a total of 434 replicates. The nail diameters tested were 6d (2.77 mm), 8d (3.38 mm), and 16d (4.24 mm). The species groups (Basswood, Douglas fir, and

[1]Research General Engineer, USDA Forest Service, Forest Products Laboratory, 1 Gifford Pinchot Dr., Madison, WI 53726 (corresponding author). E-mail: drammer@fs.fed.us

[2]Materials Engineer, USDA Forest Service, Forest Products Laboratory, 1 Gifford Pinchot Dr., Madison, WI 53726. E-mail: szelinka@fs.fed.us

Note. This manuscript was submitted on October 28, 2013; approved on March 27, 2014; published online on July 17, 2014. Discussion period open until December 17, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Structural Engineering***, © ASCE, ISSN 0733-9445/04014134(7)/$25.00.

Table 1. Withdrawal Test Matrix

Nail type	Manufacturer	Steel type	Diameter (mm)	Length (mm)	Wood species	Average specific gravity[a]	Number of tested specimens
Smooth	A	316	2.77	40.8	Basswood	0.367	50
		—	—	—	Douglas fir	0.480	50
		—	—	—	Southern pine	0.584	48
		316	3.38	65.2	Basswood	0.367	49
		—	—	—	Douglas fir	0.480	48
		—	—	—	Southern pine	0.589	47
		316	4.20	91.0	Basswood	0.367	49
		—	—	—	Douglas fir	0.482	45
		—	—	—	Southern pine	0.584	48
	B	304	3.38	77.1	Douglas fir	0.487	50
	C	304	3.40	39.5	Douglas fir	0.480	50
Annular	A	316	3.38	65.2	Douglas fir	0.480	46

[a]Specific gravity is based on oven-dry weight and volume.

Southern pine) were chosen to span the specific gravity (0.31–0.55) values observed in typical residential construction. For Objective 2, approximately 50 replicates were tested from three different manufacturers for nails of the same diameter (8d) in one species (Douglas fir) for a total of 148 replicates. Brand A was manufactured with 316 stainless steel, while Brands B and C used 304 stainless steel. For Objective 3, 46 replicates were tested for an annularly threaded diameter nail (3.40-mm shank diameter) in Douglas fir.

Prior to testing, the 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 nail and length were taken with electronic calipers to the nearest 0.025 mm. For the annularly threaded nails, both the shank and crest diameter were measured.

Lumber was conditioned at 20°C and 65% relative humidity to achieve an equilibrium moisture content of approximately 12% prior to withdrawal testing. 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 hand-driven into the lumber to a depth equal to 70% of the nail length. For annularly threaded nails, the depth of penetration did not exceed the threaded portion of the fastener. Pilot holes were used in Southern pine wood to facilitate insertion of the nail. Pilot hole diameters conformed to NDS (AWC 2012) and were 65% of the nail shank diameter. After the test, oven-dry specific gravity and moisture content measurements were determined according to ASTM D2395-93 (ASTM 1999a) and ASTM D4442-92 (ASTM 1999b) using pieces cut from the end of the source material.

Nail Bending Yield Strength

Fastener bending yield tests were conducted according to ASTM F1575-03 (ASTM 2008a) using only smooth shank nails. Thirty replicates for all three diameters of Manufacturer A and one diameter of Manufacturer B were tested. Tests for Manufacturer C could not be completed because the overall length of the fastener was shorter than the required test span. Tests were concluded when midspan deformation exceeded 2.54 mm for the smallest test span and 3.18 mm for all other spans. The deformation criteria ended all of the tests; no nails were broken or achieved a defined maximum load.

Results

Tables 1 and 2 summarize the results of the withdrawal tests (Objectives 1–3). Table 1 lists the average specific gravities, based on oven-dry weight and volume, for the wood specimen used in testing. Table 2 lists the average nail penetration, maximum test load, calculated immediate mean withdrawal strength, and coefficient of variation for each withdrawal test condition.

Fig. 1 shows the withdrawal load-deflection data between a smooth nail and an annularly threaded nail. The data were taken

Table 2. Experimental Results for Stainless Steel Withdrawal Tests

Nail type	Manufacturer	Diameter	Wood species	Nail penetration (mm)	Maximum load (N)	Withdrawal strength	
						Average (N/mm)	Coefficient of variation (%)
Smooth	A	2.77	Basswood	27.8	235	8.48	32.9
		—	Douglas fir	27.7	480	17.34	32.0
		—	Southern pine	27.1	620	22.87	32.6
		3.38	Basswood	38.8	434	11.19	34.3
		—	Douglas fir	37.7	815	21.70	38.3
		—	Southern pine	38.9	931	23.46	29.1
		4.20	Basswood	58.5	722	12.35	34.8
		—	Douglas fir	59.2	1293	21.79	40.8
		—	Southern pine	58.6	1421	24.26	30.1
	B	3.38	Douglas fir	49.2	980	19.91	37.1
	C	3.40	Douglas fir	25.9	575	22.19	38.1
Annular	A	3.38	Douglas fir	44.7	2639	59.11	27.4

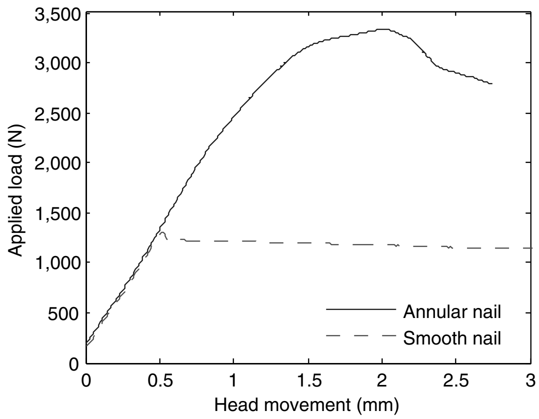

Fig. 1. Withdrawal load-deformation curves for 3.39-mm-diameter smooth and annular nails from Manufacturer A

from nails driven into the same source block. For the annularly threaded nails, the curve shows a linear region that gradually becomes nonlinear as it approaches the maximum load. After the maximum load was reached, the applied load decreased steadily until the testing was concluded. Smooth shank nails showed a linear relationship between load and displacement until a 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. Finally, the figure clearly illustrates the increased capacity of threaded nails compared to smooth shank nails.

Table 3 summarizes the fastener bending yield data (Objective 4). To obtain the yield load, a linear regression analysis was conducted on the data between 5 and 15% of the maximum load (P_m) to approximate the initial slope of the load-deformation curve. The slope was then offset an amount equal to 5, 10, 25, and 50% of the diameter of the fastener used in testing. Maximum nail bending yield load was defined as the load at the end of the test.

Discussion

The study was conducted to compare the withdrawal and bending yield strength of stainless steel to excepted values for plain carbon steel nails. Two additional objectives were to examine differences between manufacturers in the withdrawal strength of stainless steel nails and to compare the withdrawal strength of threaded stainless steel fasteners to both smooth shank stainless steel and threaded carbon steel fasteners. For three of these objectives (manufacturer, bending yield strength, and threaded nails), no large differences were found. However, large and statistically significant differences were found between the smooth shank stainless steel nails and withdrawal equations for plain carbon steel fasteners. This section will briefly discuss manufacturer, threaded fasteners, and bending yield strength before moving on to comparisons of the stainless steel withdrawal data with existing design equations and the development of a new regression equation for these data.

Manufacturer

Table 2 gives the mean withdrawal strength and coefficient of variation (COV) values for 8d (3.38-mm-diameter and 3.40-mm-diameter) for stainless steel nails obtained from three different manufacturers and withdrawn from Douglas fir. Because the mean values are similar and the COVs are high, it is likely that the manufacturing process has little or no effect on smooth stainless steel nail withdrawal strength. To validate this observation, an ANOVA of the data, at a 0.05 level of significance, was completed. This analysis revealed no statistically difference of the average withdrawal strength from the three different manufacturing sources.

Threaded Nails

Comparing the 8d (3.38-mm-diameter) threaded and smooth nail withdrawal strength from Douglas fir in Table 2 shows that threaded nail withdrawal strength is at least 2.5 times more than the smooth shank capacity. The NDS recently adopted an equation for calculating this increased withdrawal design value for post-frame ring shank nails (AWC 2012). This NDS expression is based on the following expression that predicts the average experimental withdrawal strength:

$$W = 77.51G^2D \quad (1)$$

where W = average maximum withdrawal 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; and D = shank diameter of nail (mm). To use the previous expression for design, the threaded nail must meet the post-frame ring shank nails thread manufacturing tolerances given in ASTM F1667-05 (ASTM 2008b).

For each test replicate, the predicted maximum withdrawal strength can be determined by inputting the source wood specific gravity and measured shank diameter. Using this predicted strength along with the experimental withdrawal strength, a ratio was determined for each test replicate. The average individual ratio was 0.95. A paired t-test of the predicted and experimental withdrawal strength also indicated no significant difference at a 0.05 level of confidence. This suggests that the NDS expression for post-frame ring shank nails could be applied to this specific threaded stainless steel nail, if the thread characteristics meet ASTM F1667-05 (ASTM 2008b) specifications, and that the frictional characteristic of the nail is not important for threaded nails.

Table 3. Nail Bending Yield Values at Different Offset Levels

			Maximum			Fastener bending yield at various offsets (MPa)				
Manufacturer[a]	Diameter (mm)	Test span (mm)	Load (N)	Coefficient of variation (%)	Deformation (mm)	5%	10%	25%	50%	Maximum
A	2.77	31.8	515	3.5	3.43	832	929	1,025	1,091	1,160
	3.38	38.9	723	2.3	3.68	762	861	965	1,032	1,082
	4.19	48.3	1,071	2.3	5.87	743	829	929	996	1,054
B	3.38	38.9	677	3.1	4.52	641	747	864	934	1,019

[a]Manufacturer A used 316 stainless steel, and Manufacturer B used 304 stainless steel.

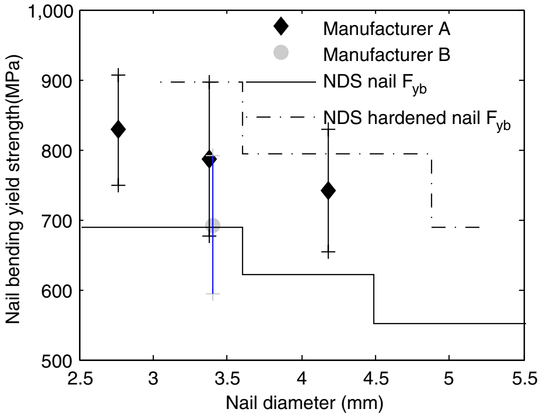

Fig. 2. Comparison of bending yield strength relative to NDS values for Manufacturer A and Manufacturer B smooth shank stainless steel nails

Nail Bending Yield Strength

Loferski and McLain (1991) sampled box nails at four locations in the United States directly from manufacturers. In total, box nails from 11 different manufacturers were tested. This work was used to establish *point in time* appropriate fastener bending yield strength inputs for use in the NDS (AWC 2012). The American Forest and Paper Association (AFPA 1999) lists bending yield strength at the 5% diameter offset and maximum levels. For common and box steel nails, the 5% offset and ultimate yield strengths are 689 and 896 MPa, respectively, for nails with diameters less than 3.61 mm (0.142 in.) and 621 and 793 MPa, respectively, for nails with diameters between 3.61 mm (0.142 in.) and 4.50 mm (0.177 in.). For hardened threaded nails, the nail bending yield strength is 25–30% higher than for common steel nails.

Fig. 2 plots the nail bending yield strength (taken from the 5% offset) as a function of nail diameter and compares it with the associated values from the NDS for both standard and hardened nails. The data error bars represent 95% confidence levels. The fasteners from Manufacturer A are slightly greater than the NDS values; those from Manufacturer B are approximately equal to the NDS relationship. Based on a comparison of both the yield and ultimate strengths of 316 (Manufacturer A) and 304 (Manufacturer B) stainless steel, greater nail bending yield values for Manufacturer A seem justified. It appears that for lateral design, the current NDS 5% offset nail bending yield inputs can be used for stainless steel nails.

Withdrawal Strength of Smooth Nails

Design values published in the NDS (AWC 2012) are based on research using bright, common degreased smooth shank nails. The original work mostly focused on 2.51 mm (7d) smooth shank nails, but additional sizes were included to investigate nail size effects (Forest Products Laboratory 1965). Based on this research, the following expression was developed to relate withdrawal strength, specific gravity, and nail diameter:

$$W = KG^{2.5}D \tag{2}$$

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 9.52 N/mm^2 (1,380 lb/in.^{2}), Eq. (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 (AFPA 1999). When K is taken as 47.57 N/mm^2 (6,900 lb/in.^{2}), Eq. (2) represents the average immediate withdrawal strength (FPL 2010).

Fitting a broader data set using nonlinear regression methods, McLain (1997) arrived at a similar expression for withdrawal strength but found a better fit when the strength had a nonlinear dependence on diameter

$$W = CG^{2.24}D^{0.84} \tag{3}$$

where C = empirical constant that equals 56.98 N/mm$^{1.84}$ (4,925 lb/in.$^{1.84}$).

For each test, the ratio of the experimental withdrawal strength to the predicted withdrawal strength was calculated for the FPL (2010) [Eq. (2)] and McLain (1997) [Eq. (3)] expressions with the corresponding nail diameter and source block specific gravity. The ratios listed in Table 4 represent the average of the individual test ratios. Ratios lower than 1 indicate that the withdrawal prediction is greater than the experimental value. Because the FPL (2010) expression [Eq. (2)] is the foundation of the NDS withdrawal formula, the following comparison is limited to experimental-to-FPL (2010) predicted ratios. Table 4 shows that as the specific

Table 4. Ratios of Experimental Withdrawal Strength to Equations to Predict Withdrawal Strength [FPL (2010) Eq. (2) and McLain (1997) Eq. (3)]

					Eq. (2)		Eq. (3)	
Nail type	Manufacturer	Diameter (mm)	Wood species	Measured withdrawal strength (N/mm)	Predicted strength (N/mm)	Ratio	Predicted strength (N/mm)	Ratio
Smooth	A	2.77	Basswood	8.48	11.09	0.78	14.54	0.59
		—	Douglas fir	17.34	21.51	0.83	26.34	0.67
		—	Southern pine	22.87	34.92	0.68	40.68	0.58
		3.38	Basswood	11.19	13.57	0.84	17.21	0.67
		—	Douglas fir	21.70	30.38	0.81	31.56	0.68
		—	Southern pine	23.96	43.55	0.57	49.05	0.50
		4.20	Basswood	12.35	16.85	0.75	20.63	0.60
		—	Douglas fir	21.79	37.69	0.69	37.74	0.59
		—	Southern pine	24.26	53.83	0.47	58.60	0.42
	B	3.38	Douglas fir	19.91	27.95	0.73	32.50	0.63
	C	3.40	Douglas fir	22.19	26.88	0.84	31.79	0.70
Annular	A	3.38	Douglas fir	59.11	N/A	N/A	N/A	N/A

Note: N/A = not applicable.

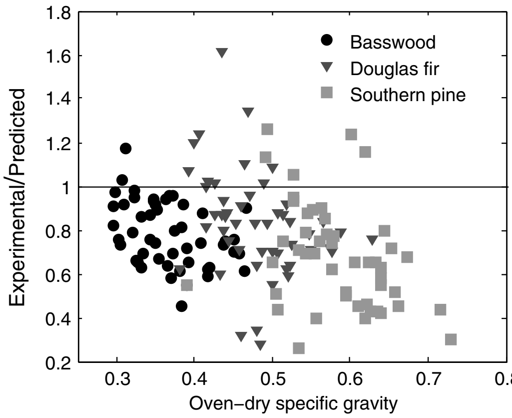

Fig. 3. Ratio of the immediate withdrawal strength to predicted withdrawal strength for 2.77-mm-diameter stainless steel nails

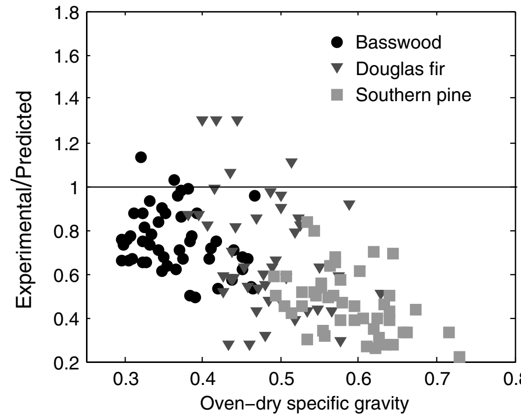

Fig. 5. Ratio of the immediate withdrawal strength to predicted withdrawal strength for 4.19-mm-diameter stainless steel nails

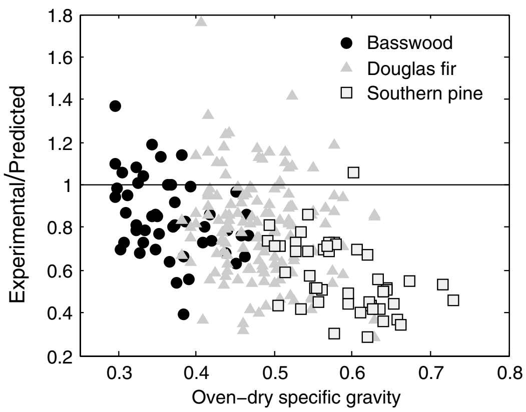

Fig. 4. Ratio of the immediate withdrawal strength to predicted withdrawal strength for 3.39-mm-diameter stainless steel nails (Douglas fir data combine the withdrawal capacity of three nail manufacturers)

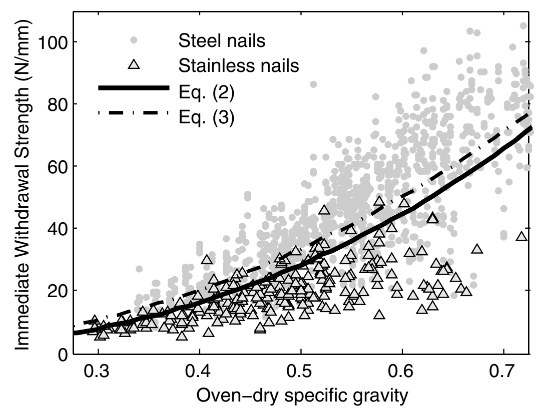

Fig. 6. Comparison of carbon and stainless steel immediate smooth shank 3.39-mm-diameter nail withdrawal capacity along with Eq. (2) [FPL (2010)] and Eq. (3) [McLain (1997)] predicted capacity

gravity increases, the ratio decreases. Nail diameter seems to be a secondary influence, with the prediction for larger-diameter nails in Southern pine having the lowest ratios.

Figs. 3–5 plot the ratio of the experimental-to-FPL predicted [Eq. (2)] withdrawal strength. Comparing the figures, the data appear to shift downward at the greatest fastener diameter. This can be most easily analyzed by comparing the number of replicates with a ratio greater than 1. For the 6d and 8d nails, 12 and 14% of the replicates were greater than 1, respectively. For the 16d nails, however, only 5% of the data were greater than 1. This decrease for the 16d nails suggests that the linear dependence of withdrawal strength on diameter in the FPL (2010) expression is not correct for the stainless steel fasteners. This is not surprising, as McLain (1997) found similar results for common steel nails.

Figs. 3–5 show that most of the experimental values are lower than the predicted values. Furthermore, as the specific gravity increases, the ratio of experimental-to-predicted values decreases—that is, the amount of overprediction is greater at higher specific gravities. Fig. 6 shows both the stainless steel experimental and historical steel withdrawal strength values versus specific gravity for only the 3.38-mm (0.131-in.)–diameter nails. Overlaid curves on the figure represent the FPL (2010) expression [Eq. (2)] and McLain (1997) expression [Eq. (3)] for 3.38-mm (0.131-in.)-diameter nails. Fig. 6 clearly shows that the withdrawal capacity for stainless steel fasteners is lower than common steel nails of equivalent diameter; the difference is greatest for wood with a higher specific gravity.

Stainless steel fasteners have shown to be corrosion-resistant in preservative-treated lumber, and Southern pine is one of the most commonly treated species (Zelinka and Rammer 2009). From a withdrawal strength perspective, this represents a worst-case scenario because the FPL (2010) expression overpredicts the withdrawal strength of stainless steel nails the most for high-specific-gravity wood species such as Southern pine. This large overprediction of strength compromises the factor of safety if the current NDS expression is used to predict stainless steel nail withdrawal.

Stainless Steel 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:

$$W = AG^b D^c \tag{4}$$

where G = specific gravity on an oven-dry basis; D = shank diameter; and A, b, and c = fitting parameters. A similar approach will be used for stainless steel nails.

Table 5. Comparative Performance of Equations from Nonlinear Least-Squares Regression of Withdrawal Data

Regression equation	Equation number	r^2	Mean percentage difference	Percentage square error	Range of mean percentage difference	Absolute mean deviation
$47.57G^{2.5}D$	2	—	−27.0	35.9	−77 to 75	30.5
$56.98G^{2.24}D^{0.84}$	3	—	−39.6	43.8	−78 to 41	40.2
$37.32G^{1.49}D^{0.32}$	5	0.49	−2.0	30.6	−66 to 117	24.0

A nonlinear regression was performed on the previous expression using all 532 smooth stainless steel withdrawal test results. The coefficient of determination (r^2), mean percentage deviation (MPD), percentage square error (PSEE), and absolute mean deviation (AMD) were all determined to assess how well the expressions model the relationship of withdrawal strength to specific gravity and diameter. The MPD, PSEE, and AMD statistics were calculated for the FPL (2010) and McLain (1997) expressions to establish a baseline (Table 5). Not surprisingly, these equations do not fit the data well. The MPDs for both the FPL (2010) and McLain (1997) common steel withdrawal strength expressions are negative, indicating that the stainless steel nails have lower withdrawal values than the equations predict.

Based on all the model fitting statistics, the following expression best fits the stainless steel withdrawal data:

$$37.32G^{1.49}D^{0.32} \tag{5}$$

where $r^2 = 0.49$; MPD $= -2$; and PSEE $= 30.6$. These values indicate a better prediction than the other expressions shown in Fig. 6 for a 3.38-mm (0.131-in.)–diameter nail.

The expression in Eq. (5) can be used to adjust the experimental withdrawal data to a common specific gravity and make a statistical comparison of the withdrawal strength of stainless steel and steel fasteners. The following relationship was use to adjust the data:

$$\frac{W_{\bar{g}}}{W_i} = \frac{37.32D^{0.32}G_{\bar{g}}^{1.49}}{37.32D^{0.32}G_i^{1.49}} = \frac{G_{\bar{g}}^{1.49}}{G_i^{1.49}}$$

where G_g = average group specific gravity; W_g = withdrawal strength adjusted to the average group specific gravity; G_i = individual replicate specific gravity; and W_i = withdrawal strength of the individual replicate. This adjustment removes the variability of specific gravity between individual replicates.

Table 6 gives the average and coefficients of variation for the adjusted withdrawal strengths. These coefficients of variation are typical of withdrawal strength results. A z-test with a 0.01 level of confidence was conducted on the adjusted withdrawal data. The results of the z-test indicate that for all wood species and nail diameters, stainless steel withdrawal strength is statistically different than common steel nails.

Extension to Other Types of Nails

Fig. 6 shows that material friction properties significantly affect the withdrawal characteristics of the smooth shank nails. Instead of conducting experiments and developing new expressions for each material used in nails, it would be more productive to relate Eqs. (3) and (4) to friction values. The simplest possible relationship would be

$$W = \frac{\mu_N}{\mu_{\text{steel}}} AG^b D^c$$

where μ_N and μ_{steel} = static coefficients of friction for a general material to wood and steel to wood, respectively, and the exponents from common steel are retained. If the withdrawal expression could be adjusted, only friction tests would need to be conducted. Andersson et al. (2007) determined the static coefficient of friction for pallets and different cargo truck flooring. Within their study, the dry static coefficient of friction between a planed wood pallet and stainless steel was 0.29, and the dry static coefficient of friction between a steel crate and plywood was 0.57. The steel-plywood friction value is consistent with the findings of other studies (Atack and Tabor 1958; MacKenzie and Karpovich 1968) for friction values between steel and wood. Assuming that these values are representative friction values, the FPL (2010) and McLain (1997) coefficients were adjusted accordingly. Fig. 7 shows the 3.39-mm-diameter withdrawal data with the best-fit expression and the frictionally adjusted FPL (2010) and McLain (1997) expressions. Although the FPL (2010) and McLain (1997) friction-adjusted expressions are not as good as the best-fit regression equation, they

Table 6. Z-Test Comparison of Specific Gravity Adjusted Smooth Shank Withdrawal Strength to FPL (2010) Withdrawal Predictions

Manufacturer	Diameter (mm)	Wood species	Adjusted withdrawal strength (N/mm)	Coefficient of variation	z-test value	Statistical difference?
A	2.77	Basswood	8.30	18.2	−6.1256	Yes
	—	Douglas fir	17.18	26.7	−4.9487	Yes
	—	Southern pine	22.89	32.8	−8.8447	Yes
	3.38	Basswood	11.00	20.9	−4.3343	Yes
	—	Douglas fir	21.03	27.0	−4.8379	Yes
	—	Southern pine	24.01	26.0	−11.5244	Yes
	4.19	Basswood	12.07	20.8	−6.9307	Yes
	—	Douglas fir	21.68	36.5	−8.5477	Yes
	—	Southern pine	24.06	28.9	−13.9501	Yes
B	3.38	Douglas fir	19.74	31.2	−6.8440	Yes
C	3.40	Douglas fir	21.73	30.2	−4.0992	Yes

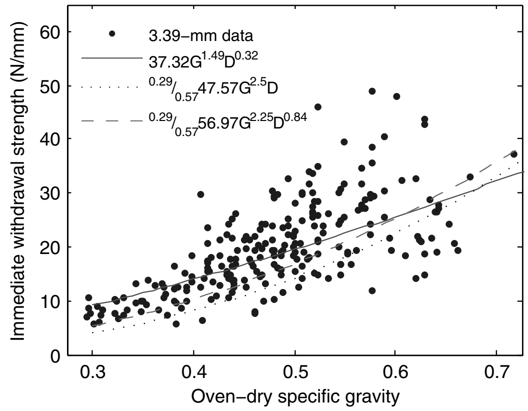

Fig. 7. Comparison of 3.39-mm-diameter best-fit equation and frictional adjusted expressions

are a better and conservative fit to the data than the original equations, which do not account for the frictional effects.

Conclusions

Withdrawal and nail bending yield tests were conducted on stainless steel fasteners to determine (1) how well current equations for smooth shank nails that use specific gravity and nail diameter as parameters predict the withdrawal strength of stainless steel nails, (2) if the manufacturing source affects the withdrawal strength of stainless steel nails, (3) the withdrawal strength of threaded ring shank nails, and (4) if the nail bending yield strength of stainless steel nails is different from prescribed design code values for steel. The following were concluded from the data presented:

- The withdrawal strength of stainless steel nails was lower than predicted based on equations developed for steel fasteners, and this difference was statistically significant. The factor of safety in the current NDS expression may be compromised at high specific gravities and large fastener diameters. A new expression for the withdrawal strength of stainless steel nails was developed.
- No appreciable differences could be found between the withdrawal strength of smooth shank stainless steel nails from different manufacturers.
- No appreciable difference in predicted withdrawal strength using the post-frame nail equation and the experimental withdrawal strength for 3.39-mm-diameter rink shank stainless steel threaded nails was observed.
- The nail bending yield strength of stainless steel nails was close to that of carbon steel nails, and the carbon steel nail bending yield expressions in the NDS can be used in the design for stainless steel nails.
- Adjusting the FPL (2010) or McLain (1997) equations by the ratio of the coefficients of friction of steel-wood and stainless steel–wood, it was possible to account for smooth shank nail withdrawal capacity due to nail material differences.

References

American Forest and Paper Association (AFPA). (1999). “General dowel equations for calculating lateral connection values.” *Technical Rep. 12*, Washington, DC, 18.

American Wood Council (AWC). (2012). “National design specification for wood construction.” *ANSI/AWC NDS-2012*, Washington, DC.

Andersson, N., Hugoson, P., Jagelčák, J., and Sökjer-Petersen, S. (2007). “Inclination tests to determine the static friction factor for different material combinations.” *Rep. No. 2007-05-14*, MarlTerm AB, Höganäs, Sweden.

ASTM. (1999a). “Standard test methods for specific gravity of wood and wood-base materials.” *D2395-93*, West Conshohocken, PA.

ASTM. (1999b). “Standard test methods for direct moisture content measurement of wood and wood-base materials.” *D4442-92*, West Conshohocken, PA.

ASTM. (2008a). “Standard test method for determining bending yield moment of nails.” *F1575-03*, West Conshohocken, PA.

ASTM. (2008b). “Standard specifications for driven fasteners: Nails, spikes, and staples.” *F1667-05*, West Conshohocken, PA.

ASTM. (2009). “Standard test methods for mechanical fasteners in wood.” *D1761-88*, West Conshohocken, PA.

Atack, D., and Tabor, D. (1958). “The friction of wood.” *Proc. R. Soc. London Ser. A, Math. Phys. Sci.*, 246(1247), 539–555.

Forest Products Laboratory. (1965). “Nail withdrawal resistance of American woods.” *Res. Note FPL–RN–093*, U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 5.

Forest Products Laboratory. (2010). “Wood handbook—Wood as an engineering material.” *General Technical Rep. FPL-GTR-19*, Dept. of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 508.

Loferski, J. R., and McLain, T. E. (1991). “Static and impact flexural properties of common wire nails.” *J. Test. Eval.*, 19(4), 297–304.

MacKenzie, W. M., and Karpovich, H. (1968). “The frictional behavior of wood.” *Wood Sci. Technol.*, 2, 139–152.

McLain, T. E. (1997). “Design axial withdrawal strength from wood. 11. Plain-shank common wire nails.” *For. Prod. J.*, 47(6), 103–109.

Rammer, D. R., and Mendez, A. M. (2008). “Withdrawal strength of post-frame ring shank nails.” *Frame Building News*, 59–67.

Rammer, D. R., Winistorfer, S. G., and Bender, D. A. (2001). “Withdrawal strength of threaded nails.” *J. Struct. Eng.*, 10.1061/(ASCE)0733-9445(2001)127:4(442), 442–449.

Skulteti, M. J., Bender, D. A., Winistorfer, S. G., and Pollock, D. G. (1997). “Withdrawal strength of ring-shank nails embedded in Southern pine lumber.” *Trans. ASAE*, 40(2), 451–456.

Zelinka, S. L., and Rammer, D. R. (2009). “Corrosion rates of fasteners in treated wood exposed to 100% relative humidity.” *J. Mater. Civ. Eng.*, 10.1061/(ASCE)0899-1561(2009)21:12(758), 758–763.