

WITHDRAWAL STRENGTH OF RING-SHANK NAILS EMBEDDED IN SOUTHERN PINE LUMBER

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ABSTRACT. Ring-shank nails are used extensively in post-frame construction due to their superior performance, yet surprisingly little testing has been done on nail sizes above 12d. Experience in the post-frame industry suggests that published allowable design values for ring-shank nails may be overly conservative and need revision. The goal of the research reported herein was to characterize the withdrawal strength of ring-shank nails embedded in Southern Pine lumber. Three sizes of galvanized and ungalvanized (bright) ring-shank nails from two manufacturers were studied. Ring-shank nails had approximately twice the withdrawal resistance of smooth-shank nails of the same diameter. Galvanizing slightly reduced withdrawal strength (approximately 8%) due to partial filling of the threads. Nail head pull-through was studied as a possible failure mode. Even allowing for galvanizing and head pull-through, strong evidence is presented for increasing withdrawal design values for ring-shank nails. **Keywords.** Nail, Withdrawal, Ring-shank, Threaded, Annular

Ring-shank nails, also known as pole-barn or annularly threaded nails, are widely used in post-frame construction and other demanding engineering applications. Ring-shank nails are a type of deformed shank nail in which circular threads are rolled into the shank after the point and head are formed. The threads provide superior withdrawal strength under extreme loading conditions and adverse moisture conditions.

The available data for withdrawal strength of ring-shank nails is sparse. Most research has focused on small-diameter nails (such as those used in the pallet industry) and relatively little data exist for sizes greater than 12d (Wills et al., 1996). In the absence of comprehensive test data, conservative engineering judgement was used to assign design values found in the 1991 and earlier editions of the *National Design Specification for Wood Construction* (NDS) (AF&PA, 1991). The rationale for these allowable stress design (ASD) values is that the smaller shank diameter of the threaded nails (when compared to common nails of the same pennyweight) is directly offset by the gripping action of the

threads. Experience in post-frame construction indicates these withdrawal values may be overly conservative (Geisthardt et al., 1991). Research is needed to determine the withdrawal strength of ring-shank nails of sizes relevant to the post-frame industry to provide a basis for revising allowable design values.

A new load and resistance factor design (LRFD) procedure has recently been approved for wood structures (ASCE, 1995). This procedure is based on structural reliability concepts; however, LRFD design parameters were obtained by calibration with the existing ASD design methodology. To advance the state-of-the-art towards true reliability-based design, sufficiently large and representative sample sizes are needed to characterize resistance distributions. However, much of the research on threaded nail performance in the past was based on sample sizes inadequate for characterizing probability distributions (Melrose, 1965; Quackenbush, 1977; Feldborg, 1989).

All of these concerns highlight the need for more test data on ring-shank nails, especially sizes greater than 12d. Such testing will facilitate assessment of the current ASD design procedures, as well as provide large sample sizes for the long-term goal of true reliability-based design.

OBJECTIVES

The objectives of this research were as follows:

1. Measure withdrawal resistance values for ring-shank nails embedded in Southern Pine lumber for both galvanized and ungalvanized (bright) nail diameters of 3.76 mm (0.148 in.), 4.50 mm (0.177 in.), and 5.26 mm (0.207 in.).
2. Characterize the variability in the withdrawal data and identify candidate probability distributions which adequately fit the data for eventual use in reliability-based design.
3. Critically evaluate the currently published allowable design values for withdrawal resistance of ring-shank nails in Southern Pine lumber.

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4. Examine nail head pull through as a possible failure mode in a common roof purlin-to-truss chord connection, with the 2x4 purlin edgewise on top of the chord and fastened with one 60d bright ring-shank nail.

BACKGROUND INFORMATION

RING-SHANK vs COMMON NAILS

When superior withdrawal capacity of a connection is required, such as in a roof purlin-to-truss connection loaded in wind uplift, ring-shank nails are favored over smooth-shank nails. Smooth-shank nails rely solely on frictional forces between the nail shank and the wood fibers to resist withdrawal loading. After the smooth shank nail is driven, stress relaxation of the wood fibers occurs, which results in loss of withdrawal strength. Ring-shank nails, however, rely on the gripping action of threads into the wood fibers, rather than friction forces alone. During driving, the wood fibers slide over the threads into the annular grooves like wedges, and the nail is released only when these fibers are torn (Stem, 1956a). Therefore, over time, the withdrawal strength of ring-shank nails decreases only slightly when compared to smooth-shank nails (Stem, 1956b; Quackenbush, 1977).

All of the past studies which compared the performance of threaded nails to common nails showed that threaded nails, particularly ring-shank nails, had a greater resistance to withdrawal loading. In most of these studies, tests were conducted on smaller diameter nails and unfortunately nail thread characteristics such as thread crest or root diameters were not reported (e.g., Ehlbeck, 1976; Quackenbush, 1977; Stem, 1956b).

ASTM F1667-95 (1995d), which is a revision of Federal Specification FF-N-105B (1977), is the primary nail manufacturing standard in the United States. The size and shape requirements in ASTM F1667-95 include pennyweight (d), nail length, head diameter, wire diameter, and thread crest diameter. Lacking in this standard are requirements for length of threaded shank, thread depth and thread shape. The only other consensus standard that deals with threaded nails is the NDS which specifies that threaded nails must be of high carbon steel and heat-treated and tempered for published NDS design values to apply (AF&PA, 1991). Additional details on nail standards and classification systems are given in Wills et al. (1996).

ORIGIN OF NAIL WITHDRAWAL DESIGN VALUES

Nail withdrawal design values published in the NDS are based on extensive testing conducted at the United States Forest Products Laboratory prior to 1931 (FPL, 1931, 1965). These tests were conducted on bright, common, degraded nails with smooth shank surfaces, driven into wood with no visible splitting (USDA, 1987). The following equation was developed based on these tests (AF&PA, 1993):

$$W = K G^{5/2} D \quad (1)$$

where

W = nail allowable design value per unit of length of penetration [N/mm (lb/in.)]

K = empirical constant which accounts for safety, experience and duration of load (K = 9.515 for SI units and 1380 for English units)

G = specific gravity of main member holding the nail point, based on oven-dry weight and volume

D = shank diameter of nail [mm (in.)]

This equation has been used to establish design values since the 1944 edition of the NDS, and it represents the average ultimate withdrawal test value divided by a factor of 5 to adjust for test conditions, safety, duration of load and experience (AF&PA, 1993). The equation for allowable values considers only specific gravity and nail diameter, and has no provisions for deformed shanks or nail coatings. During the 1970s, the Forest Products Laboratory revised specific gravity data to be based on oven-dry weight and volume at 12% moisture content. The constant factor, K, for the equation based on volume at 12% moisture content is K = 10.82 for SI units and K = 1570 for English units.

In the 1962 edition of the NDS, rules for assigning design values to threaded nails were established. The Commentary on the National Design Specification for Wood Construction (AF&PA, 1993) provides a brief explanation of how these rules were established. As previously mentioned, threaded nails have smaller diameters than common nails of the same pennyweight, which results in less contact area between the nails and the wood fiber. However, it is assumed that the gripping action of the nail threads in the wood fiber offsets the effect of the smaller shank diameter. Hence the judgement was made to assign threaded nails the same withdrawal value as common nails of the next higher diameter. This results in threaded nails having the same withdrawal design values as common nails of the same pennyweight in the range 8d to 20d.

The NDS recognizes the superior performance of threaded nails compared to smooth nails under conditions of variable wood moisture content. During cyclic moisture conditions, wood fibers expand and contract and lose contact with the nail shank, resulting in a 75% reduction in allowable withdrawal design capacity for smooth-shank nails (AF&PA, 1991). When using a threaded nail, the wood fibers remain locked in the nail threads and no decrease in allowable design value is required.

PROCEDURES

PHASE I - WITHDRAWAL TESTING

Ring-shank nails were obtained from two manufacturers identified in an informal survey of the post-frame building industry. Nails with poorly defined threads were culled as a means of establishing a lower limit for thread quality for eventual use in standardization. However, even after culling, thread quality varied significantly, with average thread depths of 0.20 to 0.33 mm (0.008 to 0.013 in.) for the groups tested. Groups of 60 ring-shank nails were tested from both manufacturers for each of the following sizes: 3.76 mm (0.148 in.) diameter 16d bright, 3.76 mm (0.148 in.) diameter 16d galvanized, 4.50 mm (0.177 in.) diameter 20d bright, 4.50 mm (0.177 in.) diameter 20d galvanized, and 5.26 mm (0.207 in.) diameter 60d bright. Additionally, a group of 3.76 mm (0.148 in.) diameter 12d bright smooth-shank common nails was tested for comparison with the 16d bright ring-shank nails of the same diameter. Nails were

degreased using mineral spirits and dried before testing as specified in ASTM D 1761-88 (1995a).

Sixty, 2×6 No.1 Southern Pine pieces were obtained from a local lumber manufacturer. The lumber was conditioned to an equilibrium moisture content of approximately 12% on a dry-weight basis. Withdrawal testing was conducted in accordance with ASTM Standard D 1761-88 (1995a). Nails were hand-driven approximately 70% of their length into the narrow face of the lumber. None of the specimens were predrilled. Before driving each nail, care was taken to avoid defects such as knots or wane on the edge of the board into which the nail was being driven. All specimens were tested within one hour after fabrication. Following withdrawal testing, specific gravity tests were performed on each lumber specimen following ASTM Standard D 2395-93, Method A (1995b).

PHASE II — NAIL HEAD PULL-THROUGH TESTING

Testing was performed to examine head pull-through as a possible failure mode in a common roof purlin to truss chord connection with the 2×4 purlin edgewise on top of the chord. The purpose of these tests was to gain insights about one particular type of connection that is widely used in post-frame construction. A comprehensive examination of nail head pull-through as a function of penetration depth, head size, wood specific gravity, etc. was beyond the scope of this study.

Thirty Southern Pine 2×6s were selected to simulate the upper truss chords and 15 Spruce-Pine-Fir and 15 Western Woods 2×4s were used for the purlins. The rationale for selecting wood species was to test a worst-case scenario for nail head pull-through by using relatively low density lumber for the purlin attached to a high-density truss chord. The lumber was at approximately 12% moisture content at the time of fabrication and testing. Thirty connections were assembled with 5.26 mm (0.207 in.) diameter 60d bright ring-shank nails. No lumber specimens were predrilled. Care was taken to avoid driving the nails through any visible defects in the lumber. All specimens were tested within one hour after fabrication.

RESULTS AND DISCUSSION

PHASE I

Ultimate Withdrawal Values. Average withdrawal strengths and coefficients of variation (Coir) for the 12d common and 5 groups of ringshank nails are presented in table 1. The withdrawal strength of the 3.76 mm (0.148 in.) diameter 16d ring-shank nails was approximately twice as great as the withdrawal resistance of the same diameter 12d common nails. Similar results were found in several other

studies (Quackenbush, 1977; Melrose, 1965; Ehlbeck, 1976; Stem, 1956b). Coefficients of variation for the ring-shank nails were remarkably similar across groups. Galvanizing had a slight negative effect on average withdrawal strength due to partial filling of the threads.

Load-Displacement Curves. A typical load-displacement plot encountered in withdrawal testing of the ring-shank and smooth nails is shown in figure 1. The graph depicts the load versus displacement for a 3.76 mm (0.148 in.) diameter 16d bright ring-shank nail versus a 12d smooth-shank common nail with the same diameter and driven the same depth in the same piece of Southern Pine lumber. This graph is typical of most of the load-displacement curves observed during testing. The initial slope before the maximum withdrawal load is reached is generally steeper for the ring-shank nails. The threaded nail takes a substantially higher load before ultimate failure is reached. The distinguishing characteristic between the two load curves occurs after ultimate load. The mechanism by which the smooth-shank nail resists withdrawal is friction. When ultimate load is reached, withdrawal resistance becomes a function of the dynamic coefficient of friction rather than the static coefficient of friction which controls withdrawal performance before ultimate load is reached. The connection is still able to carry a large portion of the ultimate load due to frictional contact. Conversely, the load-carrying ability of the ring-shank nail connection after ultimate load is reached is greatly reduced. The failure mechanism of the ring-shank nail connection is tearing of the wood fibers between the threads. Once ultimate load is surpassed, only a small frictional force between the wood fibers in the threads and the surrounding tom fibers remains to resist load.

Probability Distribution Fitting. Summary statistics, including skewness and kurtosis, were calculated for each of the nail groups together with frequency histograms to assess candidate probability distributions. Some of the nail groups exhibited slight positive skew while others were nearly symmetric. Probability distributions that were investigated include the normal, two-parameter lognormal and two-parameter Weibull.

The GDA software package (Worley et al., 1990), which uses the method of maximum likelihood to fit distributions to data sets, was used to estimate the parameters of the

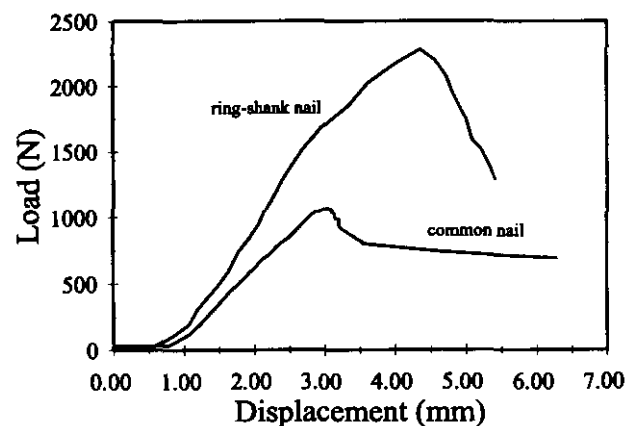


Figure 1—Typical load-displacement curves for common and ring-shank nails of the same diameter.

Table 1. Summary of nail withdrawal test results for Southern Pine lumber

Nail Group	Sample Size	Ultimate Withdrawal Strength	
		Average N/mm(lb/in.)	Coef. of Variation
0.148 in.-diameter, 12d common, bright	60	33.3 (190)	0.29
0.148 in.-diameter, 16d ring-shank, bright	120	64.3 (367)	0.27
0.148 in.-diameter, 16d ring-shank, galvanized	120	60.1 (343)	0.23
0.177 in.-diameter, 20d ring-shank, bright	120	76.0 (434)	0.23
0.171 in.-diameter, 20d ring-shank, galvanized	120	69.4 (3%)	0.24
0.207 in.-diameter, 60d ring-shank, bright	60	83.0 (474)	0.23

Table 2. Probability distributions for ultimate withdrawal strength data (N/mm) for ring-shank nails in Southern Pine

Nail Group	Best Fitting Distribution	Probability Distribution Parameters	
		Scale	Shape
0.148 in.-diameter, 16d ring-shank, bright	Weibull	70.95	4.01
0.148 in.-diameter, 16d ring-shank, galvanized	Weibull	65.61	4.80
0.177 in.-diameter, 20d ring-shank, bright	lognormal	4.21	0.249
0.177 in.-diameter, 20d ring-shank, galvanized	lognormal	4.30	0.226
0.207 in.-diameter, 60d ring shank, bright	Weibull	90.56	5.04

normal, Weibull and lognormal distributions for each of the five test groups. The respective probability density functions were overlaid on the histograms of the data for visual appraisal of the goodness-of-fit of the distributions. Additionally, the Anderson-Darling and Kolmogorov-Smirnov goodness-of-fit tests were conducted.

The Weibull was the best-fitting distribution for the 60d bright ring-shank nails, and the 16d bright and galvanized ring-shank nails. The lognormal provided the best fit for the 20d bright and galvanized ring-shank nails. All of the proposed distributions passed both statistical goodness-of-fit tests at a significance level of 0.10. It should be noted that the normal distribution would have been acceptable for all of the data sets based on the results of the K-S test with a significance level of 0.10, but did not pass the A-D tests due to lack of fit in the distribution tails. Best fitting probability distribution parameters are summarized in table 2.

Evaluation of Current Design Values. As previously discussed, the current practice for determining nail withdrawal design values is to divide the average ultimate withdrawal strength by a factor of 5. When this same methodology was applied to the results of this study, an increase of 36 to 48% was observed over published design values for the bright ring-shank nails as shown in table 3. Galvanized nails showed an increase of 34 to 38% following the same procedure.

Another method of deriving allowable design values, commonly used for lumber, involves calculating the 5% tolerance limit of the population at a confidence level of 75% (ASTM, 1955c). While the tolerance limit approach is not currently used to calculate design values for fasteners, we include it here as a possible means of incorporating more consistent safety and reliability throughout structural systems. Tolerance limits can be estimated parametrically or non-parametrically. The parametric method requires the underlying probability distribution to be specified, whereas the non-parametric method requires no assumption about the distribution and therefore gives more conservative tolerance limit estimates. In either case, the sample must be

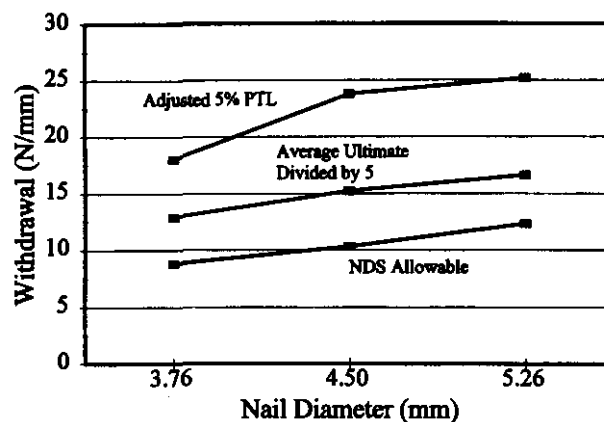


Figure 2-Comparison of NDS allowable, adjusted average ultimate, and adjusted 5% PTL for 20d bright ring-shank nails.

sufficiently large and representative of the total population. Five percent tolerance limits are then divided by a factor of 2.1 to account for load duration and safety. For clarity of presentation we define this allowable design value as the *adjusted 5% parametric tolerance limit (PTL)*.

The adjusted 5% PTL values for the 5 ring-shank nail groups, given in table 3, were between 102 and 130% greater than the NDS allowable design values. NDS allowable design values, adjusted 5% PTL and adjusted average ultimates (i.e., divided by 5) are illustrated in figure 2 for the three sizes of bright ring-shank nails. A histogram of ultimate withdrawal strength for the 20d bright ring-shank nails together with the adjusted 5% PTL and adjusted average ultimates (divided by 5) are plotted in figure 3 to illustrate their relative magnitudes compared to the test data. Even if published ring-shank nail withdrawal design values were increased 30%, the values would still be over three standard deviations away from the average ultimate withdrawal values from this research.

PHASE II

Nail Head Pull-Through Testing. As noted previously, relatively low density lumber species were selected for the roof purlins and higher density lumber for the truss. The rationale was to increase the likelihood of nail head pull-through failures. The average specific gravity of the 15 Spruce-Pine-Fir and the 15 Western Woods 2×4s was 0.45 (based on oven-dry weight and volume). The 30 Southern Pine 2×6s had an average specific gravity of 0.56. For all three species groupings, the specific gravities were similar to the nominal values given in the NDS.

A statistical summary of the purlin-to-truss connection tests is given in table 4. Of the 30 specimens tested,

Table 3. Comparison of NDS design values, average ultimate withdrawal strength divided by 5, and adjusted 5% parametric tolerance limits for ring-shank nails in Southern Pine

Nail Group	NDS Allowable* N/mm (lb/in.)	Average Ultimate Strength Divided by 5 N/mm (lb/in.)	Adjusted 5% Parametric Tolerance Limit† N/mm (lb/in.)
0.148 in.-diameter, 16d ring-shank, bright	8.8 (SO)	12.9 (73.6)	18.0 (103)
0.148 in.-diameter, 16d ring-shank, galvanized	8.8 (SO)	12.0 (68.8)	17.9 (102)
0.177 in.-diameter, 20d ring-shank, bright	10.3 (59)	15.2 (87.0)	23.8 (136)
0.177 in.-diameter, 20d ring-shank, galvanized	10.3 (59)	13.9 (79.2)	20.8 (119)
0.207 in.-diameter, 60d ring-shank, bright	12.3 (70)	16.6 (95.0)	25.2 (144)

* Allowable ring-shank withdrawal design value in Southern Pine with a specific gravity of 0.55.

† 5% exclusion limit at 75% confidence, divided by adjustment factor of 2.1.

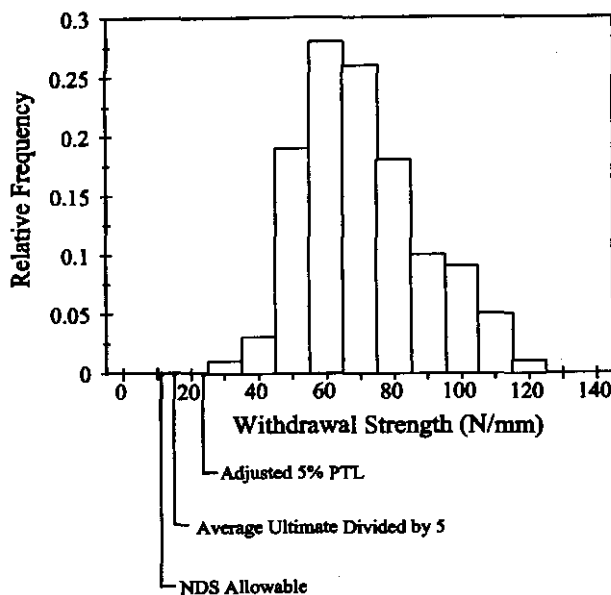


Figure 3-Distribution of withdrawal strength for 4.50 mm (0.177 in.) diameter 20d bright ring-shank nails

10 failed in nail withdrawal and 20 failed in nail head pull-through. Following the connection tests, the 20 Southern Pine specimens with nails still intact were subjected to the same withdrawal test used in Phase I to determine what the ultimate withdrawal values would have been had the specimens not failed in head pull-through. The average connection strength (including head pull-through and withdrawal failure modes) was 85% of the average withdrawal strength of 30 nails embedded in Southern Pine. However, the effect of nail head pull-through on the adjusted 5% PTL was less than 4%. This phenomenon can be explained by observing the distribution of the connection data in figure 4. The upper tail of the histogram is cropped due to the specimens which failed in head pull-through; however, the left tail (which has the greatest impact on structural integrity) was not greatly affected. Again, the NDS allowable withdrawal design value, adjusted average ultimate test value (divided by 50 and the adjusted 5% PTL are plotted in figure 4 to facilitate a comparison with the connection test data. For the nails and lumber species tested, nail head pull-through was a dominant failure mode; however, it did not have a significant effect on design values computed using a tolerance limit approach.

SUMMARY AND CONCLUSIONS

The main goal of this study was to test the withdrawal strength of ring-shank nails in Southern Pine lumber and to

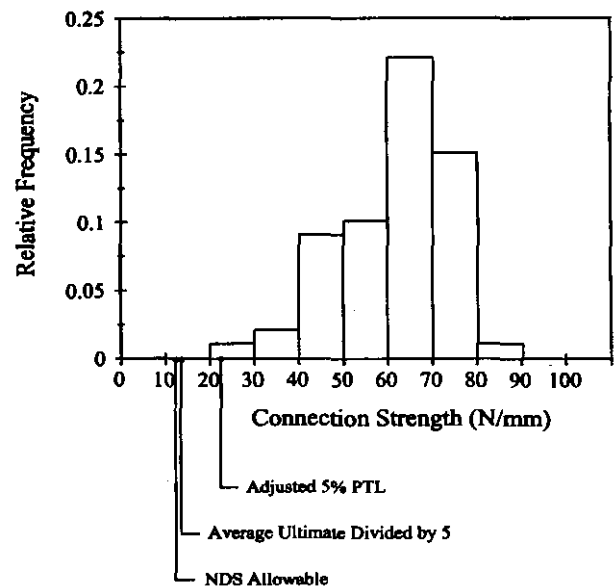


Figure 4-Distribution of ultimate strength of roof purlin-to-truss connections using 5.26 mm (0.207 in.) diameter 60d bright ring-shank nails.

compare the results with published design values. Three sizes of galvanized and bright ring-shank nails were studied: 3.76 mm (0.148 in.) diameter, 4.50 mm (0.177 in.) diameter, and 5.26 mm (0.207 in.) diameter. Additionally, 3.76 mm (0.148 in.) diameter smooth-shank common nails were tested to facilitate a comparison with ring-shank nails of the same diameter. The average thread depths of the ring-shank nails varied from 0.20 to 0.33 mm (0.008 to 0.013 in.) for the five groups.

Ring-shank nails had nearly twice the withdrawal strength of smooth-shank nails of the same diameter. Galvanizing slightly reduced withdrawal strength (approximately 8%) due to partial tilling of the threads. Based on the current method for calculating allowable withdrawal design values, the adjusted test results were over 34% greater than published design values. An alternate statistical method gave results that supported even greater increases in allowable design values for ring-shank nail withdrawal.

Probability distributions, which are needed for reliability-based design, were fit to each of the data sets. Visual appraisal, as well as Anderson-Darling and Kolmogorov-Smirnov tests, were used to assess goodness-of-fit for each of the proposed distributions. The Weibull and lognormal distributions provided the best fits overall.

Additional tests were performed to examine head pull-through as a possible failure mode in a common roof purlin to truss chord connection with the 2×4 purlin edgewise on

Table 4. Statistical summary of simulated roof purlin-to-truss connection tests

Failure Mode	Ultimate Strength N/mm (lb/in.)		Average Strength Divided by 5 N/mm (lb/in.)	Adjusted 5% PTL * N/mm (lb/in.)
	Average	Coefficient of Variation		
Connection strength (including nail head pull-through failures)	66.0 (377)	0.16	13.2 (75.4)	22.2 (127)
Withdrawal strength of 30 nails embedded in Southern Pine	77.8 (444)	0.20	15.6 (88.8)	23.1 (132)

* 5% exclusion limit at 75% confidence, divided by adjustment factor of 2.1.

top of the chord. Purlins were from low density lumber and truss chords were from high density lumber to increase the likelihood of nail head pull-through. Nail head pull-through caused a slight reduction in the average connection strength; however, the effect on the statistical tolerance limit method for deriving withdrawal design values was minimal.

The results of this study support an increase in allowable withdrawal design values for ring-shank nails; however, any adjustment should be linked with a specification of minimum acceptable thread characteristics. In addition, the effects of galvanization and nail head pull-through on connection strength should be considered when determining how much of an increase is prudent. Currently, the NDS specifies that threaded nails shall be made of "hardened-steel" and typical nail bending yield strengths are given (AF&PA, 1991). Similarly, ring-shank nail design values could be increased for nails meeting minimum acceptable thread requirements. To facilitate change in published allowable design values, results of this ongoing research project are being shared with nail manufacturers and technical committees responsible for wood design standards such as the NDS.

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