TABLE 5
DOWEL BENDING AND BEARING STRENGTH PROPERTIES FOR FULL-SCALE SYSTEM ROOF-TO-WALL CONNECTION TESTS

FASTENER DESCRIPTION	AVG SIZE[1] DIAMETER, IN, X LENGTH, IN (COV OF D, %)	AVG 5% OFFSET NAIL BENDING STRESS[1,2], $F_{B,5\%}$, psi (COV, %)	AVG ULTIMATE NAIL BENDING STRESS[1,2], $F_{B,ULT}$, psi (COV, %)	AVG 5% OFFSET DOWEL BEARING STRESS[3], $F_{E,5\%}$, psi		AVG ULTIMATE DOWEL BEARING STRESS[3], $F_{E,ULT}$, psi	
				Main (SPF)	Side (SYP)	Main (SPF)	Side (SYP)
8d bright common nails[4]	0.131 x 2.5 (0.4)	81,491 (8.8)	108,772 (6.2)	3,075	6,093	4,976	7,405
12d bright pneumatic nails[5] full round head	0.120 x 3.25 (0.1)	90,596 (4.4)	126,726 (2.3)	3,075	6,093	5,050	7,516
16d bright pneumatic nails[5] full round head	0.132 x 3.25 (0.7)	83,691 (3.4)	118,300 (3.2)	3,075	6,093	4,969	7,395

[1]Average of 10 samples of each nail type.
[2]Nails were tested using the following spacings between the reaction points: 8d common – s = 1.75 in, 12d pneumatic – s = 2.5 in, and 16d pneumatic – s = 2.5.
[3]Calculated based on average measured specific gravity for main members and side members.
[4]Common nails (Brand: Grip-Rite Fas'ner) distributed by Primesource Building Products, Inc., Dallas, Texas.
[5]Pneumatic nails manufactured by Senco Products, Inc., Cincinnati, Ohio. The nails were coated with a plastic-polymer coating by the manufacturer.

TABLE 6
DOWEL BENDING AND BEARING STRENGTH PROPERTIES FOR INDIVIDUAL ROOF-TO-WALL CONNECTION TESTS

FASTENER DESCRIPTION	AVG SIZE[1] DIAMETER, IN, X LENGTH, IN (COV OF D, %)	AVG 5% OFFSET NAIL BENDING STRESS[1,2], $F_{B,5\%}$, psi (COV, %)	AVG ULTIMATE NAIL BENDING STRESS[1,2], $F_{B,ULT}$, psi (COV, %)	AVG 5% OFFSET DOWEL BEARING STRESS[3], $F_{E,5\%}$, psi		AVG ULTIMATE DOWEL BEARING STRESS[3], $F_{E,ULT}$, psi	
				Main (SPF)	Side (SYP)	Main (SPF)	Side (SYP)
8d bright common nails[4]	0.131 x 2.5 (0.4)	81,491 (8.8)	108,772 (6.2)	4,301	4,301	6,047	6,047
16d bright pneumatic nails[5] full round head	0.132 x 3.25 (0.7)	83,691 (3.4)	118,300 (3.2)	4,301	4,301	6,040	6,040

[1]Average of 10 samples of each nail type.
[2]Nails were tested using the following spacings between the reaction points: 8d common – s = 1.75 in and 16d common – s = 2.75 in.
[3]Calculated based on average tested specific gravity (oven-dry) for main members and side members.
[4]Common nails (Brand: Grip-Rite Fas'ner) distributed by Primesource Building Products, Inc., Dallas, Texas.
[5]Pneumatic nails manufactured by Senco Products, Inc., Cincinnati, Ohio. The nails were coated with a plastic-polymer coating by the manufacturer.

4.0 EXPERIMENTAL RESEARCH PROGRAM

4.1 TASK 1 – RAFTER-TO-CEILING JOIST CONNECTION (HEEL JOINT) TESTS

4.1.1 Objective

The objective of Task 1 was to measure the performance of heel joints assembled using the minimum nailing schedules allowed by the prescriptive building code provisions [31][32] for residential construction with interpretations representative of the field framing practices. A heel joint configuration with an increased number of nails was also tested to investigate the response of dense nailing patterns required by the recent changes in the building code provisions for high-load applications [32]. Common and pneumatic nails were investigated to measure the potential differences in the behavior of traditional hand-driven and newer power-driven nails. In addition, results were examined to evaluate a capacity-based design methodology for analysis of nailed connections. Test results were used to determine the scope of the minimum allowed prescriptive provisions for heel joint construction for selected building configurations and loading conditions.

4.1.2 Experimental Approach

A series of pictures (Figure 1) shows the setup for rafter-to-ceiling joist connection test. A test specimen consisted of two parallel trusses paired into a roof system assembly. Therefore, each specimen included a total of four rafter-to-ceiling joist connections to investigate the performance of a multiple heel joint system. Each truss was framed with two 2 inch by 8 inch nominal size SPF rafters and a 2 inch by 6 inch nominal size SPF ceiling joist. The testing was performed using the universal test machine (UTM) with the compression load applied at the ridge joint at a constant rate of displacement of 0.2 inch/min. The specimens were set on double 2 inch by 4 inch nominal size top plates which simulated rafter bearing on a light-frame wood wall.

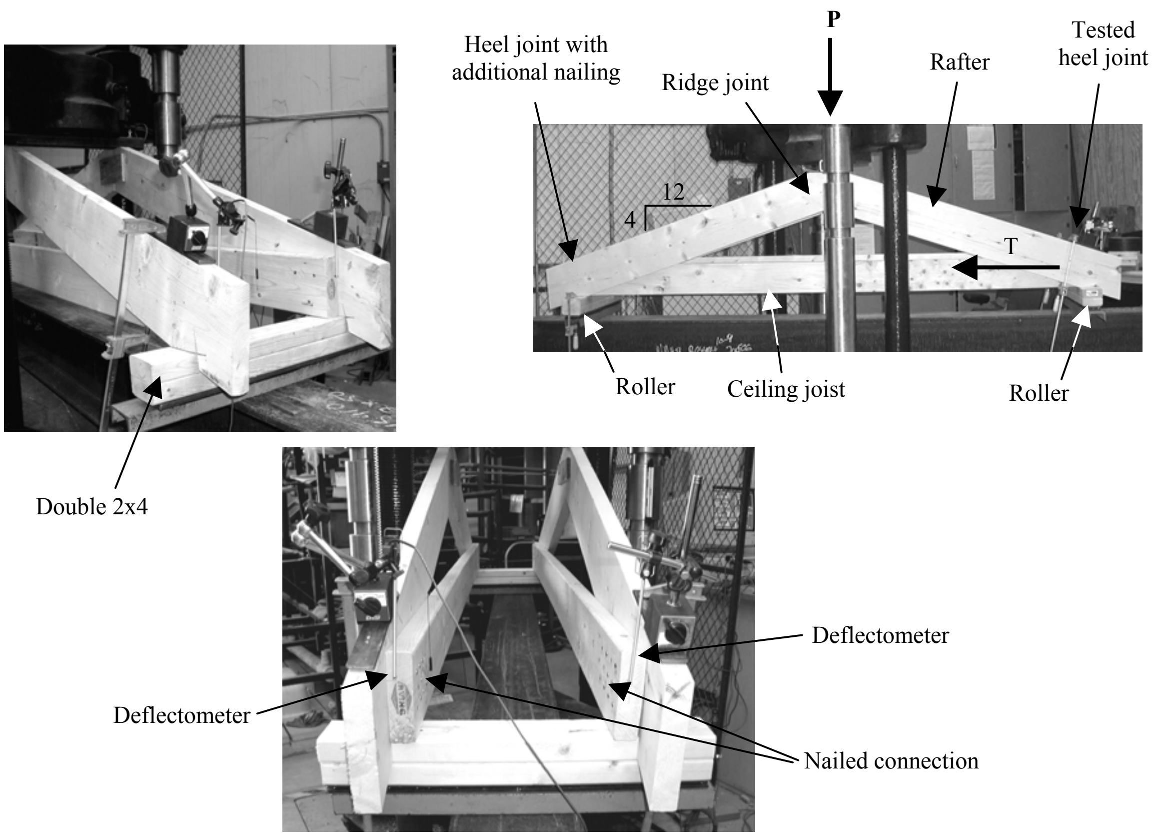


Figure 1
Rafter-to-Ceiling Joist Connection Test Setup and Instrumentation

Five connection configurations were tested with varying fastening schedules (Table 7). Specimen configurations 1, 3, and 5 were tested without mechanical fasteners between the top plates and the specimens (unattached), whereas specimen configurations 2 and 4 were testes with the rafters and ceiling joists toe-nailed to the top plates (attached). Heel joint configuration 5 with 12 nails per joint was investigated to evaluate recent changes to connection requirements for residential construction.

TABLE 7
SPECIMEN CONFIGURATIONS FOR RAFTER-TO-CEILING JOIST CONNECTION TESTS

CONFIG. #	RAFTER-TO-JOIST CONNECTION[1]	TEST SPECIMEN	METHOD OF CONNECTING TO THE TOP PLATE	SAMPLE SIZE (PAIRS)
1	3-10d Common Nails	2 x 6 Ceiling Joist face-nailed to 2 x 8 Rafters	Unattached	6
2	3-10d Common Nails	2 x 6 Ceiling Joist face-nailed to 2 x 8 Rafters	Attached with 3-8d Common Toe-Nails per Joint	6
3	3-16d Pneumatic Nails	2 x 6 Ceiling Joist face-nailed to 2 x 8 Rafters	Unattached	6
4	3-16d Pneumatic Nails	2 x 6 Ceiling Joist face-nailed to 2 x 8 Rafters	Attached with 3-16d Pneumatic Toe-Nails per Joint	6
5	12-16d Pneumatic Nails	2 x 6 Ceiling Joist face-nailed to 2 x 8 Rafters	Unattached	2

[1]For actual nail sizes, refer to Section 4.1.

Three toe-nails per joint were used to connect the rafter-ceiling joist assemblies to the top plate in the "attached" tests (Table 7). Therefore, the force transferred between the ceiling joist and rafter through the top plate was limited by the member receiving one toe-nail to the top plate.

The load was applied through a 2-inch square steel distribution beam that spanned the paired trusses at the ridge joint. The distribution beam was rigidly fixed to the UTM crosshead so that equal displacements were applied to each rafter to more closely represent the behavior of rafters and heel joints within a sheathed roof system. A 2 inch by 4 inch piece of oriented strand board was nailed to the interior surface of the ridge joint to temporarily brace the assembly until it was secured in the UTM. Roller plates under the double top plates at both reactions allowed horizontal movement of the specimens at the heel joints.

Horizontal displacement of the rafter relative to the ceiling joist was measured with a deflectometer[1]. Displacements were measured for two heel joints on one side of the specimen (Figure 1) and, to ensure that failure occurred at one of these two joints, the number of nails was doubled for the joints on the opposite side of the specimen. Each test was run until the maximum load occurred and a downward trend in load was observed. Load and displacement

[1]Deflectometers were manufactured by Instron – Satec Systems, Grove City, PA.

measurements were collected by the UTM data acquisition system. Following each test, one nail from the connection was isolated and the wood joint was split apart to identify the failure mode.

Calculation of the loads used in the analysis was based on the assumption that the applied load, P (Figure 1), was equally distributed between the opposite sides of each specimen. The tension force in the ceiling joist was the force resisted by the nails at the heel joint. The lateral load resisted by a system of two parallel heel joints was calculated as follows:

$$T = \frac{1}{2}\frac{P}{Tan(\theta)} \tag{8}$$

where:

P = applied compression load;
Tan(θ) = slope of the rafter relative to the ceiling joist, and,
T = total tension force in two ceiling joists.

T was used in analysis of the results and to plot the load-deformation relationships on the basis of a system of two parallel heel joints.

4.1.3 Results and Discussion

Figures 2 through 6 show the load-deformation curves for heel joint connection tests of paired rafter-ceiling joist systems. Because response of an individual connection can not be separated from the system response of two parallel joints due to unique stiffness characteristics of each joint, the load-deformation relationships for a system of two parallel heel joints located on the right side of the assembly (Figure 1) are presented. The load is calculated using Equation 8. The deformation of a system of two parallel heel joints is assumed to be the average deformation of two individual joints. Throughout this section, results are reported and discussed for the system of two parallel heel joints unless specified otherwise.

Table 8 summarizes the performance parameters for five tested configurations of heel joint systems including the peak load, load at 0.015-inch joint slip, and load determined based on 5 percent nail diameter offset limit state. Peak load for heel joints assembled with 3-10d common and 3-16d pneumatic nails exhibited only a marginal difference for both attached (2,830 lb vs. 2,698 lb) and unattached (2,212 lb vs. 2,277 lb) configurations. The heel joint with 12-16d pneumatic nails (Configuration 5) exhibited an increase in the average peak load by a factor of 3.7 relative to heel joint with 3-16d pneumatic nails (Configuration 3). This increase in the connection capacity corresponded to about an 8 percent decrease in the per-nail unit resistance. Although the decrease in the unit capacity can be due to the inherent variability of material properties between the specimens, it can be the result of the dense nailing pattern that promotes premature wood splitting as observed in some specimens.

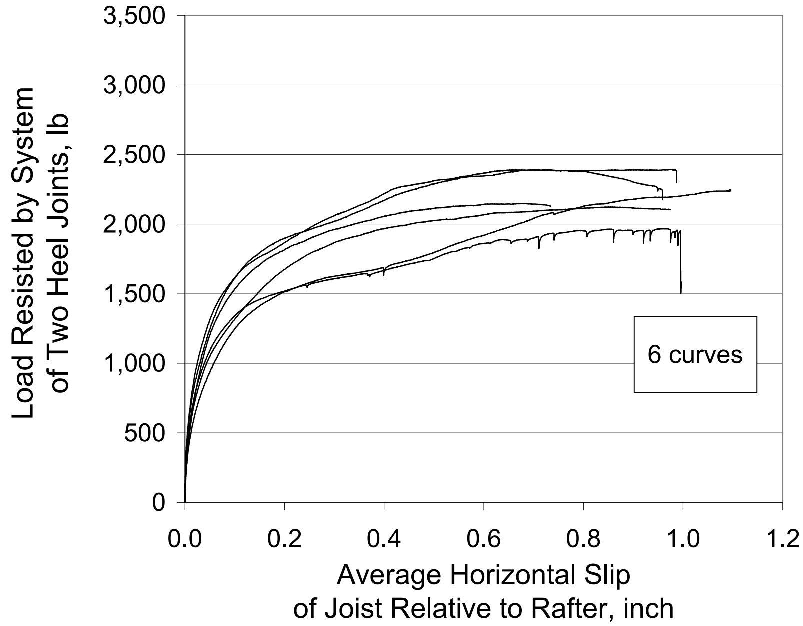


Figure 2
Load-Deflection Relationship for a System of Two Parallel Heel Joints with 3-10d Common Nails per Joint (Members are Unattached to Top Plate) – Configuration 1

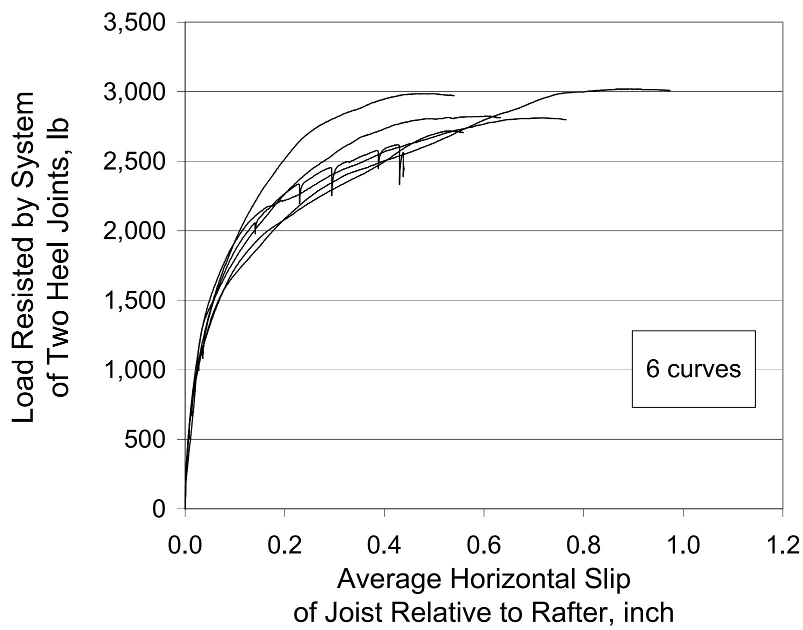


Figure 3
Load-Deflection Relationship for a System of Two Parallel Heel Joints with 3-10d Common Nails per Joint (Each Joint is Attached to Top Plate with 3-8d Common Nails) – Configuration 2

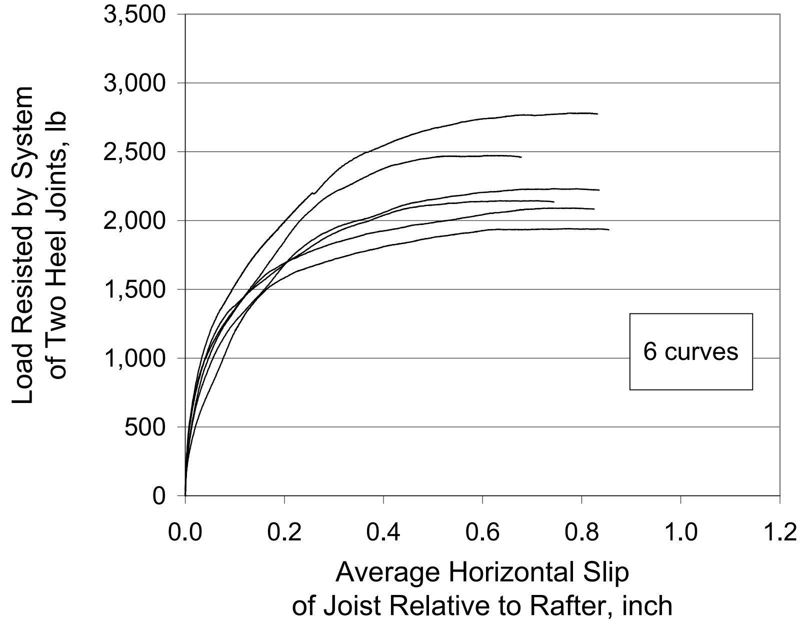


Figure 4
Load-Deflection Relationship for a System of Two Parallel Heel Joints with 3-16d Pneumatic Nails per Joint (Members are Unattached to Top Plate) – Configuration 3

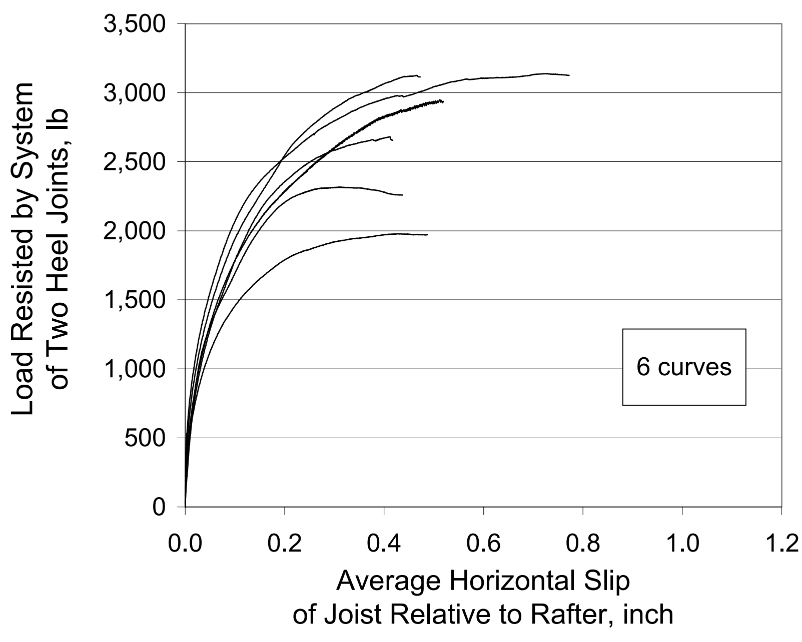


Figure 5
Load-Deflection Relationship for a System of Two Parallel Heel Joints with 3-16d Pneumatic Nails per Joint (Each Joint is Attached to Top Plate with 3-16d Pneumatic Nails) – Configuration 4

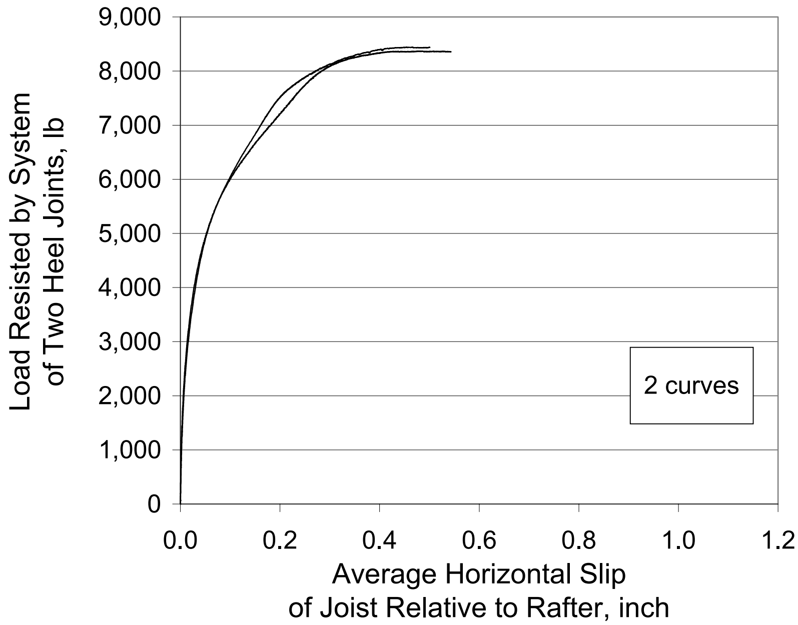


Figure 6
Load-Deflection Relationship for a System of Two Parallel Heel Joints with 12-16d Pneumatic Nails per Joint (Members are Unattached to Top Plate) – Configuration 5

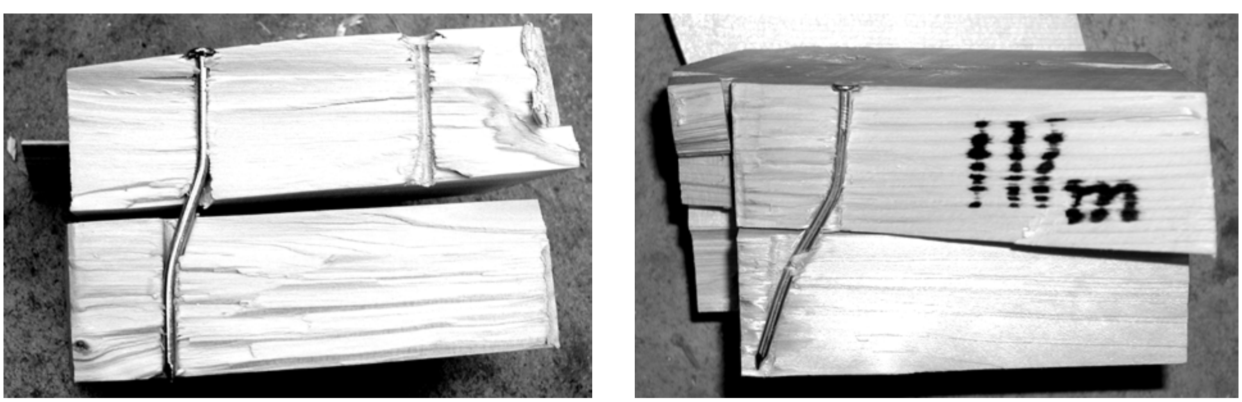
TABLE 8
SUMMARY OF TEST RESULTS FOR RAFTER-TO-CEILING JOIST CONNECTION TESTS

CONFIG. #	RAFTER-TO-JOIST CONNECTION	SAMPLE SIZE (PAIRS)	METHOD OF CONNECTING TO THE TOP PLATE	PEAK LOAD[1]		LOAD[1] @ 0.015 IN. SLIP		LOAD[1] @ 5% NAIL DIAMETER OFFSET	
				Mean, lb	COV, %	Mean, lb	COV, %	Mean, lb	COV, %
1	3-10d Common Nails	6	Unattached	2,212	7.5	687	13.5	708	9.4
2	3-10d Common Nails	6	Attached with 3-8d Common Toe-Nails per Joint	2,830	5.4	775	8.0	817	6.3
3	3-16d Pneumatic Nails	6	Unattached	2,277	13.3	586	16.5	592	12.4
4	3-16d Pneumatic Nails	6	Attached with 3-16d Pneumatic Toe-Nails per Joint	2,698	17.4	764	14.9	825	13.1
5	12-16d Pneumatic Nails	2	Unattached	8,406	n/a[2]	3,031	n/a[2]	2,875	n/a[2]

[1]Shear load on a system of paired joints calculated using Equation 8.
[2]COV is not reported due to small sample size.

An examination of the load-deformation relationships indicates that the attachment of the heel joint members to the top plate increases the peak lateral resistance of the heel joint (Figure 2 vs. Figure 3 and Figures 4 vs. Figure 5). The use of three 8d common nails and three 16d pneumatic nails increases the average heel joint resistance by 309 lb and 210 lb per joint, respectively (Table 8). The peak resistance of heel joints assembled with 16d pneumatic nails (D = 0.132 inch) is comparable or exceeds that for heel joints assembled with 10d common nails (D = 0.149 inch) (Table 8). This phenomenon contradicts the yield theory that predicts a strength increase of about 29 percent for 10d common nail relative to 16d pneumatic nail based on the diameter increase. This disagreement can be the result of one or more factors: improved friction between pneumatic nails and wood, increased nail bending strength of pneumatic nails (Table 4), longer nail length that increases nail gripping at large deformations, and improved bearing of pneumatically-driven nails.

Failure modes were determined for each specimen by splitting the members apart at one nail location and visually inspecting the nail and surrounding wood (Figure 7). Table 9 summarizes the observed failure modes for each tested configuration and compares that with the predictions of the yield theory. Although the yield theory predicts that all tested heel joint configurations fall into the yield mode IV category (Figure 7.a) (refer to [1],[2] for yield mode classification), deformed nail shapes with a combination of characteristics of modes III and IV (Figure 7.b) were also observed and were the predominant response modes for test configurations 1 and 3. These response modes were classified as III-IV because the main member portion of the nail developed a plastic hinge and the nail tip rotated from the initial vertical position. The former was an attribute of yield mode IV, whereas the latter was associated with yield mode III. It should be noted that the yield modes predicted with the yield theory are based on the initial deformed nail shape, whereas the test specimens were examined after joint slip of as much 1.0 inch and the associated response modes should be referred to as failure modes. The yield mode and failure mode can be different for the same connection. For example, a connection can begin initial yielding in a mode III and achieve its capacity and fail in mode IV. The asymmetry of the joint further contributed to the connection response representative of both modes. The nail head provided an additional rotation restraint which promoted the development of an ample plastic hinge in the side member, whereas the nail tip was free to slip and was only restrained against rotation by surrounding wood of the main member.



a. Failure Mode IV   b. Failure Mode III-IV

Figure 7
Failure Mode Classification

Table 9 summarizes the calculated and measured lateral load resistance at 5 percent nail diameter offset slip limit state and includes corresponding predicted yield modes and observed failure modes. The ratio of the calculated to tested values falls in the range between 1.5 and 1.9. This systematic difference between the design and measured values can be caused by a number of reasons. First, the definition of the 5 percent offset limit results in the selection of an arbitrary point on the experimental curves and is driven primarily by judgement used to identify the initial linear response region. Figure 8 depicts a series of three load-displacement charts for the same specimen plotted using three different scales for the X-axis (i.e., displacement). Because the curve is nonlinear from the origin and it lacks a well-defined yield point, three different answers are obtained for each scale. Therefore, determination of the 5 percent nail diameter offset limit state is influenced by the scale used to plot the curve and the results contain a systematic bias related to judgement of the engineer who applies the method.

Second, the 5 percent nail diameter offset bending strength of nail and dowel bearing strength of wood are established based on testing of specimens of standard geometries. However, these standard configurations may be unrepresentative of the actual connection geometry and the stress distribution within the connection. The connection slip can be either magnified or decreased relative to the standard test deformations due to the differences in geometries. Moreover, the yielding of the dowel and wood established for the standard 5 percent nail diameter offset conditions can occur "out of sync" within the connection. Combined with the lack of the explicit yield point on the load-deformation curve, this can lead to the disparity between the test and calculated values at 5 percent nail diameter offset limit state. The identified shortcomings of the 5 percent nail diameter offset method diminish the practical value of the current definition of the yield limit state for design of multiple nailed connections. As demonstrated throughout this document, the connection capacity can successfully replace the 5 percent offset yield load as the design basis.

TABLE 9
COMPARISON OF CALCULATED AND MEASURED 5 PERCENT OFFSET LIMIT VALUES

CONFIG. #	SINGLE HEEL JOINT CONNECTION	TOP PLATE ATTACHMENT	CALCULATED[1,2] 5% OFFSET LIMIT VALUE FOR A SYSTEM OF TWO HEEL JOINTS, LB	PREDICTED YIELD MODE	AVG TEST LOAD AT 5% OFFSET LIMIT STATE, LB (COV, %)	OBSERVED FAILURE MODE[4]	CALCULATED/ TEST
1	3-10d Common Nails	Unattached	1,812 1,812 **1,322**	III_m III_s **IV**	725 (10.5)	**III-IV** IV	1.82
2	3-10d Common Nail	Attached with 3-8d common toe-nails per joint	2047 2047 **1,558**	III_m III_s **IV**	817 (6.3)	**III-IV** **IV**	1.91
3	3-16d Pneumatic	Unattached	1,577 1,577 **1,057**	III_m III_s **IV**	592 (12.4)	**III-IV** IV	1.79
4	3-16d Pneumatic Nails	Attached with 3-16d pneumatic toe-nails per joint	1,869 1,869 **1,350**	III_m III_s **IV**	825 (13.1)	III-IV **IV**	1.64
5	12-16d Pneumatic	Unattached	6,308 6,308 **4,228**	III_m III_s **IV**	2,875 (n/a[3])	**IV**	1.47
						Average Ratio (COV)	1.73 (0.10)

[1]See Appendix A for calculations.
[2]For configurations 2 and 4, calculated with one of three toe-nails making a contribution to the heel joint shear resistance.
[3]COV is not reported due to small sample size.
[4]Failure mode in bold was the predominant mode.

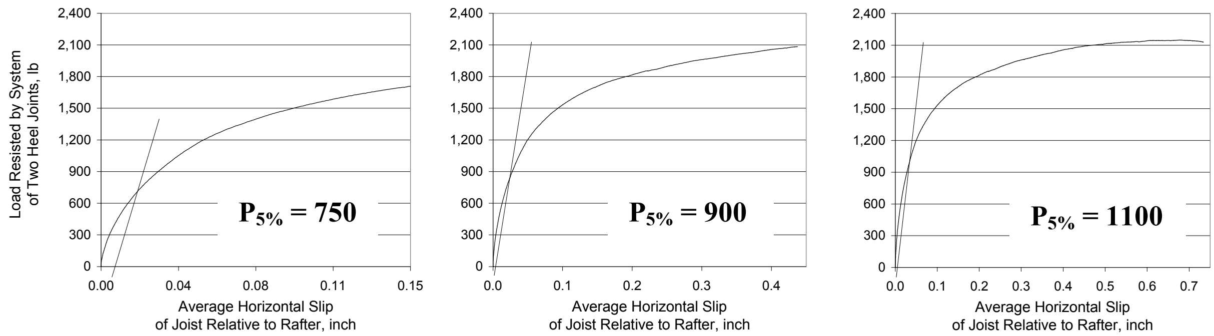


Figure 8
Determination of the 5 Percent Nail Diameter Offset Load

Table 10 compares the allowable design values calculated according to the 1997 NDS methodology with the average test load at joint slip of 0.015 inches. Because the 1997 NDS procedure is calibrated to match the historical design values established on 0.015-inch joint slip limit state (refer to Section 2.1.1), the NDS allowable design values should be consistent with the loads measured at the same slip. However, the average test loads are 28 to 46 percent lower than the NDS values with the exception of configuration 5. Therefore, the slip limit design basis established for an individual nail connection provides a similarly poor correlation with the response of a system of multiple nail connections.

TABLE 10
COMPARISON OF NDS ALLOWABLE DESIGN VALUES WITH TEST LOADS AT 0.015-INCH JOINT SLIP (NDS SLIP LIMIT BASIS)

CONFIG. #	SINGLE HEEL JOINT CONNECTION	TOP PLATE ATTACHMENT	CALCULATED NDS ALLOWABLE LATERAL DESIGN VALUE[1] FOR A SYSTEM OF TWO HEEL JOINTS, LB	AVG TEST LOAD @ 0.015 INCH SLIP, LB (COV, %)	NDS/0.015 INCH SLIP
1	3-10d Common Nails	Unattached	962	687 (13.5)	1.41
2	3-10d Common Nail	Attached with 3-8d common toe-nails per joint	1,133[2]	775 (8.0)	1.46
3	3-16d Pneumatic	Unattached	769	586 (16.5)	1.31
4	3-16d Pneumatic Nails	Attached with 3-16d pneumatic toe-nails per joint	981[2]	764 (14.9)	1.28
5	12-16d Pneumatic	Unattached	3,075	3,031 (n/a[3])	1.02
				Average Ratio (COV)	1.30 (0.13)

[1]See Appendix A for calculations.
[2]Calculated with one of three toe-nails making a contribution to the heel joint shear resistance.
[3]COV is not reported due to small sample size

The comparison of the predictions of the yield theory and test results at the ultimate load limit state (Table 11) shows that the yield theory underestimates the experimental peak loads by 16 to

32 percent. The differences between the analytical and experimental values can be attributed to the secondary effects of the connection response such as friction between wood and nail surface, nail head fixity, failure modes with ambiguous nail shape, etc. Although each of these factors contributes to the connection resistance, it does not alter the connection response mode to a degree that can create a significant inconsistency with the yield theory formulation. Therefore, the yield theory accurately models the primary connection response modes at the ultimate resistance limit state and provides the peak load estimates with the degree of accuracy sufficient for engineering analysis applications. If improved accuracy is required, the secondary effects can be incorporated into design through a series of adjustment factors.

It should be noted that the dowel bearing strength of wood was estimated using empirical equations [2] derived based on compilation and averaging of the test data for various species and specific gravity values. These equations may not accurately predict the response of the tested connections. The correlation between the yield theory and the test data is expected to improve with better estimates of the dowel bearing strength values.

TABLE 11
COMPARISON OF CALCULATED AND MEASURED ULTIMATE LOADS

Config. #	Single Heel Joint Connection	Top Plate Attachment	Calculated[1,2] Ultimate Resistance for a System of Two Heel Joints, lb	Predicted Failure Mode	Avg Ultimate Test Load, lb (COV, %)	Observed Failure Mode[4]	Calculated/ Test
1	3-10d Common Nails	Unattached	2,643 2,643 **1,859**	III_m III_s **IV**	2,212 (7.5)	**III-IV** IV	0.84
2	3-10d Common Nail	Attached with 3-8d common toe-nails per joint	2,984 2,984 **2,200**	III_m III_s **IV**	2,830 (5.4)	**III-IV** **IV**	0.77
3	3-16d Pneumatic	Unattached	2,357 2,357 **1,540**	III_m III_s **IV**	2,277 (13.3)	**III-IV** IV	0.68
4	3-16d Pneumatic Nails	Attached with 3-16d pneumatic toe-nails per joint	2,783 2,783 **1,966**	III_m III_s **IV**	2,698 (17.4)	III-IV **IV**	0.73
5	12-16d Pneumatic	Unattached	9,428 9,428 **6,160**	III_m III_s **IV**	8,406 (n/a[3])	**IV**	0.73
						Average Ratio **(COV)**	0.75 0.08

[1]See Appendix A for calculations.
[2]For configurations 2 and 4, calculated with one of three toe-nails making a contribution to the heel joint shear resistance.
[3]COV is not reported due to small sample size.
[4]Failure mode in bold was the predominant mode.

Table 12 shows a comparison of the NDS allowable lateral design values relative to the average peak loads. The results show that the NDS allowable design values provide an average safety margin relative to capacity of about 2.6. Further examination of the safety margins suggests that the connections assembled with pneumatic nails have a higher average safety margin (2.8) than that for connections with common nails (2.4). This trend was not observed for 0.015-inch slip (Table 9) and 5 percent nail diameter offset (Table 10) limit states, whereas similar conclusions could be drawn for the capacity limit state (Table 11).

The pneumatic nails used in this study (refer to Section 4.1) have a plastic polymer coating applied from the nail tip to approximately half length of the nail. The coating is a heat-activated lubricant that decreases the forces required to drive the nail into wood and also works as a glue that improves the adhesion between nail to wood. The coatings considerably improve the dowel withdrawal resistance and can increase the dowel lateral resistance at the ultimate limit state [33]. Another reason for the increased strength of pneumatic connections can be the conditions of the dowel bearing surface produced by coated pneumatic nails installed using power tools in a fraction of a second as opposed to non-coated common nails installed manually with a hammer in several strokes. Through reducing friction, the lubricant decreases stresses during the nail installation and can minimize wood splitting around the nail body. Further research is needed to quantify these effects on the lateral resistance of connections assembled with pneumatic nails.

The increased capacity of connections fabricated with coated pneumatic nails can be used as an evidence to introduce another adjustment factor for lateral and withdrawal design of nailed connections. However, the sustained long-term performance of such connections under moisture, temperature, and loading cycles should be demonstrated to allow for consideration of coating effects in design procedures.

The increased resistance can be also attributed to longer nail length of 16d pneumatic nails, L = 3.25 inch, versus 8d common nails, L = 3.0 inch. The better penetration provides addition fixity of the nail tip in the main member and improved friction, both of which can enhance the connection performance at capacity level when the nail has deformed and undergone partial withdrawal from the main member. In addition, common nails with larger diameter, D=0.149 inch, than pneumatic nails, D=0.131 inch, can promote localized splitting of wood around the nail and alter bearing conditions in the direction parallel to grain.

TABLE 12
SAFETY MARGINS RELATIVE TO NDS ALLOWABLE VALUES

CONFIG. #	**SINGLE HEEL JOINT CONNECTION**	**TOP PLATE ATTACHMENT**	**CALCULATED[1,2] NDS ALLOWABLE LATERAL DESIGN VALUE FOR A SYSTEM OF TWO HEEL JOINTS, LB**	**NDS YIELD MODE**	**AVG ULTIMATE TEST LOAD, LB (COV, %)**	**OBSERVED FAILURE MODE[4]**	**AVERAGE ULTIMATE/NDS (SAFETY MARGFIN)**
1	3-10d Common Nails	Unattached	962	**IV**	2,212 (7.5)	**III-IV** IV	2.30
2	3-10d Common Nail	Attached with 3-8d common toe-nails per joint	1,133	**IV**	2,830 (5.4)	**III-IV** **IV**	2.49
3	3-16d Pneumatic	Unattached	769	**IV**	2,277 (13.3)	**III-IV** IV	2.96
4	3-16d Pneumatic Nails	Attached with 3-16d pneumatic toe-nails per joint	981	**IV**	2,698 (17.4)	III-IV **IV**	2.75
5	12-16d Pneumatic	Unattached	3,075	**IV**	8,406 (n/a[3])	**IV**	2.73
						Average Ratio (COV)	2.64 (0.10)

[1]See Appendix A for calculations.
[2]For configurations 2 and 3, calculated with one of three toe-nails making a contribution to the heel joint shear resistance.
[3]COV is not reported due to small sample size.
[4]Failure mode in bold was the predominant mode.

4.1.4 Design Applications

This section explores the design application of test results from Task 1. The minimum allowable heel joint nailing schedule (joint configurations 1 and 2 (Table 8)) required by the prescriptive building code provisions (Table R602.3(1) [32]) are analyzed. A range of roof configurations that are considered representative of typical framing practices are used in the analysis.

Design input parameters:

Roof slope, Tan(θ)	5:12, 6:12, 7:12
Rafter spacing, s	16, 24 inches
Roof span, *l*	20, 24, and 28 feet (where 28 feet approximates the maximum allowed horizontal roof span for 2x6 rafters without intermediate bracing for ground snow load of 30 psf [32])
Dead load, D	10 psf
Load combination	Dead + Snow (D + S)
Load duration factor	1.15 – Snow load, 1.6 – Test results

Allowable resistance values, F, for individual heel joints are determined from test results of paired assemblies (Table 8). A safety factor of 2.0 relative to the joint peak load (capacity) and standard use conditions (i.e., adjustment factors equal unity except load duration factor) are used.

Configuration 1: 3-10d Common Nails Unattached F = (2,212)(1.15)/[(2)(2)(1.6)] = 398 lb
Configuration 2: 3-10d Common Nails Attached F = (2,830)(1.15)/[(2)(2)(1.6)] = 508 lb

Maximum allowable roof snow loads, determined using Equation 9, are summarized in Table 13 for the selected building geometries and heel joint configurations 1 and 2.

$$S = \frac{4\ F\ Tan(\theta)}{l\ (s/12)} - D \qquad (9)$$

TABLE 13
ALLOWABLE SNOW LOADS FOR HEEL JOINT CONFIGURATIONS 1 AND 2

Roof Slope	Rafter Spacings	Heel Joint					
		3-10d Common Nails Unattached to Top Plate (Configuration 1)			3-10d Common Nails Attached to Top Plate with 3-8d Common Nails (Configuration 2)		
		Roof Span, ft					
		20	24	28	20	24	28
		Allowable Snow Load, psf					
5:12	16	15	10	L[2]	21	16	12
	24	L	L	L	11	L	L
6:12	16	20	15	11	28	21	17
	24	10	L	L	15	11	L
7:12[1]	16	27	21	16	38	30	24
	24	14	10	L	21	16	12

[1]Allowable snow loads are increased by 10 percent to account for roof slope effects.
[2]Design is governed by live load (L). The specified joint configuration can not be used for this roof geometry and loading condition. Design assumptions: load combination = D + L, L = 15 psf, load duration factor = 1.25.

Table 13 indicates that the use of the minimum prescriptive heel joint nailing schedules should be limited to specific geographic areas and building geometries. For example, the heel joint with 3-10d common face-nails and frame members attached to the wall top plate with 3-8d common toe-nails used with rafters spaced 24 inches on center, 6:12 roof slope, and 24-foot roof span should be used only in the areas with ground snow loads of 10 psf or less. These areas generally include the southern United States unless higher snow loads are required due to local climatic conditions or high elevations. The same joint configuration used with rafters spaced 16 inches on center, 7:12 roof slope, and roof span of 24 feet can be constructed in the areas with ground snow loads up to 30 psf. This snow load exceeds or meets the design requirements for the majority of the United States with the exception of the northern states and high elevation regions. If the specified attachment of the rafter and ceiling joist to the top plate is not provided, the maximum allowable roof span should be reduced as specified for configuration 1 in Table 13.

The allowable design values included a reduction for short-term duration of the tests relative to the design load duration (2 months for snow load, and seven days for construction load) as required by the NDS [1]. This reduction was originally adopted into the provisions for analysis of wood connections from the methodologies developed for design of solid-sawn lumber under bending and axial loading. However, the applicability of load duration effects observed in solid wood members was not directly validated for wood connections. If the load duration factor is excluded from the analysis, the allowable ground snow loads reported in Table 13 can be increased accordingly.

4.1.5 Conclusions

1. Peak load for heel joints assembled with 3-10d common and 3-16d pneumatic nails exhibited only a marginal difference for both attached (2,830 lb vs. 2,698 lb) and unattached (2,212 lb vs. 2,277 lb) configurations (Table 8).

2. Attachment of the heel joint to the wall top plate with toe-nails improved the heel joint resistance. Three 8d common toe-nails increased average heel joint capacity by 309 lb, whereas three 16d pneumatic toe-nails increased average heel joint capacity by 210 lb (Table 8). The contribution of three 8d common toe-nails to heel joint resistance exceeded the yield theory predictions, whereas that for three 16d pneumatic nails was consistent with the yield theory (Table A3).

3. The performance of pneumatic nails is improved relative to common nails as shown by an increases in the average safety margin (Table 12). This effect is primarily attributed to the nail polymer coating that adheres nail surface to surrounding wood. Further research is needed to measure the long-term performance of the coatings to permit the use of the improved friction between nail and wood for design applications.

4. The observed failure modes often had characteristics attributed to yield modes III_m and IV including partial development of a plastic hinge and rotation of the nail tip in the main member of the connection (Figure 7 and Table 9). The development of this transition failure mode was due to the asymmetry of the nailed heel joint created by the nail head fixity effect in the side member of the connection.

5. The NDS allowable design load showed a poor correlation with the experimental 0.015-inch slip limit values for multiple nail connections (Table 10).

6. Use of 5 percent nail diameter offset yield load results in an arbitrary design limit that provides an inconsistent safety margin relative to the connection failure (Table 9). Moreover, the 5 percent dowel diameter offset rule for determination of the yield point is ambiguous for application to nail connections and it introduces a systematic bias in the interpretation of the test results (Figure 9).

7. The NDS yield equations, using ultimate dowel bearing and ultimate nail bending values, provided conservative estimates of the lateral capacity by a consistent margin of about 20 percent for common nails and 30 percent for pneumatic nails (Table 11). Because the observed response modes for the tested nailed connections generally agreed with the assumptions of the yield theory, this level of accuracy is sufficient for engineering design applications. Where improved accuracy is required, the contribution of secondary effects such friction and nail head fixity must be included.

8. Use of yield equations to predict ultimate capacity resulted in less variability relative to the primary design limit state related to safety (i.e., failure). The COV of the average ratio in Table 11 is lower (0.08) than the COV of the average ratio in Tables 9 (0.13) and 10 (0.10), suggesting a greater consistency in the capacity-based calculations.

9. The safety margin, measured as a ratio of the NDS allowable value to the average ultimate load, was in the range between 2.3 and 2.4 for common nails and between 2.7 and 3.0 for pneumatic nails (Table 12). It is recommended that conventional construction requirements for heel joints specified in current building codes be reevaluated based on the findings of this study using joint capacity as the design basis and a minimum safety factor of 2.0.

10. The prescriptive nailing provisions of using three 10d common nails (or equivalent) for construction of conventional heel joints should be limited by building geometry and loading condition as illustrated in Table 13. Alternatively, additional fastening should be required by analysis considering above recommendations.