U.S. Department of Housing and Urban Development
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Roof Sheathing Connection Tolerances

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Roof Sheathing Connection Tolerances

Prepared for

U.S. Department of Housing and Urban Development
Washington, DC

by

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Executive Summary

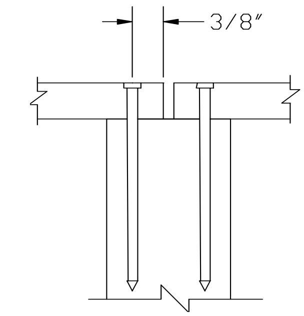
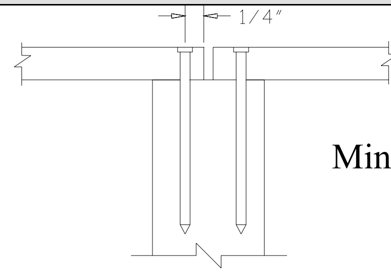
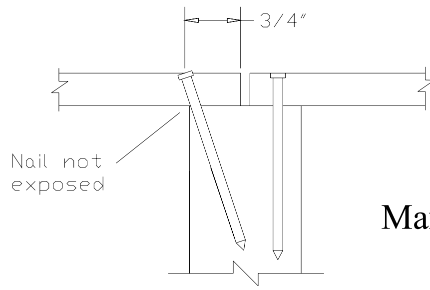
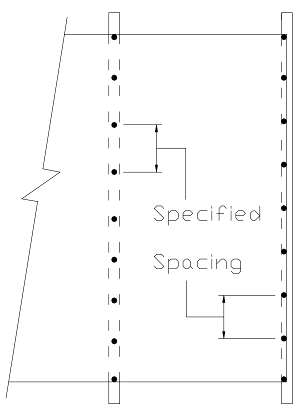
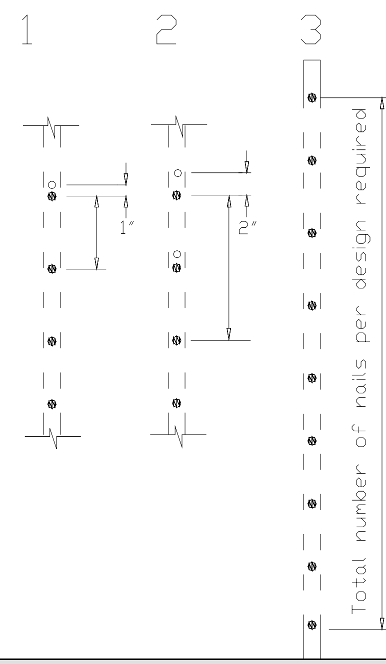
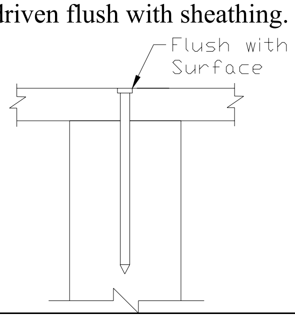
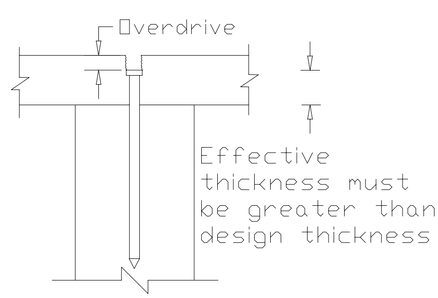
Proper attachment of structural sheathing to the roof framing is a critical step in building a wind resistant structure. Inadequate fastening of roof sheathing panels is one of the primary causes of damage to light-frame wood construction during high-wind events such as hurricanes and tornados. The current guidelines for placement of sheathing fasteners when used with 2x lumber imply the degree of accuracy that is impractical for typical construction methods. Although it is reasonable to assume that some amount of variance from these guidelines is allowed, no approved or validated range of tolerances have been established. The following are standard specifications for installing wood structural sheathing panels:

- minimum 1/8-inch gap between panel edges;
- 3/8-inch minimum edge distance;
- fastener head flush with sheathing surface; and,
- specified nail spacing (e.g., 6 inches on center).

This study addresses the need for practical roof sheathing nailing tolerances. These tolerances will allow for moderate errors in nail placement without compromising the intended strength of the sheathing connection. This testing plan was developed to establish tolerance limits for:

- nail edge distance;
- nail spacing ; and,
- nail overdrive.

The tests conducted in this research demonstrate that slight nailing discrepancies have little affect on sheathing connection capacities. Nailing tolerances, which allow for practical degrees of variation, were developed from the findings of this study for nail diameters of 0.131" or less and sheathing thickness of 7/16" or greater and are listed in the following table:

Current Guidelines	Suggested Tolerances (Nail Diameter D ≤ 0.131” and Sheathing thickness T ≥ 7/16”)
Edge Distance:	
3/8-inch from edge of panel to centerline of fastener 	***Tolerance:*** • Minimum = 1/4-inch from edge of panel to centerline of fastener  Minimum • Maximum = 3/4-inch from edge of panel to centerline of fastener and fastener angled such that no portion is exposed from the underside and the framing member remains un-split.  Maximum
Spacing Between Fasteners:	
Spacing as specified (e.g., 6 inches on center) 	***Tolerance*:** 1. Spacing between any two consecutive fasteners not to exceed specified spacing plus one inch. **and** 2. Total distance between any three consecutive fasteners not to exceed minimum spacing multiplied by two, plus two inches. **and** 3. Total number of fasteners in a nail line shall not be less than calculated using the minimum required spacing. 
Fastener Overdrive:	
Head of fastener is to be driven flush with sheathing. 	***Tolerance:*** • Overdrive allowed if sheathing has been sized thicker than required by design. Depth of penetration must be kept such that remaining thickness under the head of the nail is greater than or equal to the required thickness but shall not exceed 1/3 the thickness of the panel. 

1.0 Introduction

Proper attachment of roof structural sheathing is a critical step in building a wind resistant structure. The roof sheathing serves multiple structural functions. It provides diaphragm action to resist lateral forces, braces framing members, and provides support for the roofing material. Therefore, the roof sheathing must be properly attached to achieve the intended purpose. Inadequate fastening of roof sheathing panels is one of the primary causes of damage to light-frame wood construction during high-wind events such as hurricanes and tornados [1][2].

Factors such as fastener edge distance, overdrive, and spacing can affect both the withdrawal and shear resistance of sheathing fasteners. Yet, current guidelines for attaching sheathing panels to roof framing do not include acceptable tolerances for these fastening characteristics. Installation guidelines require a minimum 3/8-inch nail edge distance and a minimum 1/8-inch gap between adjacent panels [3]. When sheathing panels are used with 2-inch nominal width (1.5-inch actual) framing members in a manner consistent with these minimum placement specifications, the level of required precisions is such that each fastener should be located within a region less than 5/16 inch. In addition, fasteners are required to be driven flush with the surface of the panel. Because sheathing panels are typically attached using pneumatic nail guns, a certain degree of deviation from the minimum installation specification can be expected. Therefore, a set of acceptance criteria in the form of maximum allowable tolerances is needed such that both the framer and the inspector can objectively evaluate sheathing fastener installation.

The objective of this testing program is to investigate the sensitivity of the resistance of roof sheathing connections to incremental increases in deviation from the baseline installation practice for nailing characteristics including edge spacing, fastener spacing, and degree of nail over-penetration (i.e., overdrive). Based on this data, acceptable variances can be established that allow for a reasonable degree of deviation without compromising the structural integrity of the system. The recommendations developed in this testing program could be used by framers, building officials, and in framing quality programs.

The specific objectives for this test program were to:

1. Conduct uplift and shear tests of roof sheathing connections assembled with an incremental degree of deviation from the baseline scenario;
2. Compare test results with baseline resistance and with published capacities to determine the effect on strength for each level of deviation; and,
3. Use the results of the testing program to make recommendations for installation tolerances.

2.0 Testing Plan

2.1 General

Sheathing connection specimens were tested under two loading conditions: uplift and shear. Variations of each nailing characteristic (edge distance, nail spacing, and overdrive) were first tested in uplift. The variations that exhibited excessive strength loss in the uplift tests were eliminated as possible tolerance limits and not tested in shear. In addition, the nailing characteristics that only varied the spacing between fasteners were not tested in shear since the total number of nails in the shear line remained constant. Eight variations in fastener installation were tested in uplift and three variations were tested in shear. Three tests for each variation were done for uplift, and two tests for each variation were done for shear. Table 2.1 shows the test matrix for this plan.

TABLE 2.1
TEST MATRIX

NAILING CHARACTERISTIC	NUMBER OF TESTS	
	Uplift	Shear
Baseline	3	2
Edge Distance #1 (3/4-inch, angled 20°)	3	-
Edge Distance #2 (1/4-inch)	2[1]	2
Edge Distance #3 (1/8-inch)	3	-
Fastener Spacing #1 (± ½")	3	-
Fastener Spacing #2 (± 1")	3	-
Overdrive #1 (Up to 25%)	3	2
Overdrive #2 (25% to 50%)	3	-
Total Number of Tests	**23**	**6**

[1]The third test for this nailing characteristic was inadvertently not conducted.

The type of fastener used in this study was an 8d common, full round head nail (0.131" x 2-1/2"), which follows the IRC 2003 [4] specification for attaching roof sheathing. Although it is common for builders to use smaller, pneumatic nails (e.g., 0.113" x 2-3/8") for this application, the larger "common" sized nail was tested to examine potential negative effects of the larger diameter on edge distance requirements.

The following sections describe the nailing variations tested in this study.

<u>Baseline</u>

The baseline tests were used as a benchmark for this study. The specimens were constructed in accordance to panel manufacturer nail placement recommendations (i.e., 3/8 inch from the panel edge, no overdrive, and zero nail-to-nail spacing tolerance (see Figure 2.1)[3]. The nail spacing schedule followed the requirements of the IRC 2003 [4]. For one- and two-family dwellings in areas with moderate design wind speeds (i.e., less than 110 mph), 8d common nails at 6 inches on center at panel edges and 12 inches on center in the field are required for the attachment of roof sheathing. Near roof edges, ridges, and eaves (within 48 inches) the code specifies 6-inch spacing at panel edges, and 6-inch spacing in the field. The latter nailing schedule was used in this test program in order to examine the most critical case for the edge nailing. At 12-inch field spacing, the critical nail (first to fail) is invariably an intermediate field nail. This was confirmed analytically, and empirically in APA's test report T92-28 [5], which demonstrates how the tributary loading area for field nails is approximately four times greater than the tributary area for the edge nailing when 12-inch spacing is used in the field. The 6-inch field nailing criteria used for this study reduced the tributary loading ratio to approximately two (Figure 2.2) and therefore could more effectively identify potential capacity losses due to edge nailing discrepancies (e.g., close edge distances, overdriven nails, or varied nail-to-nail spacing).

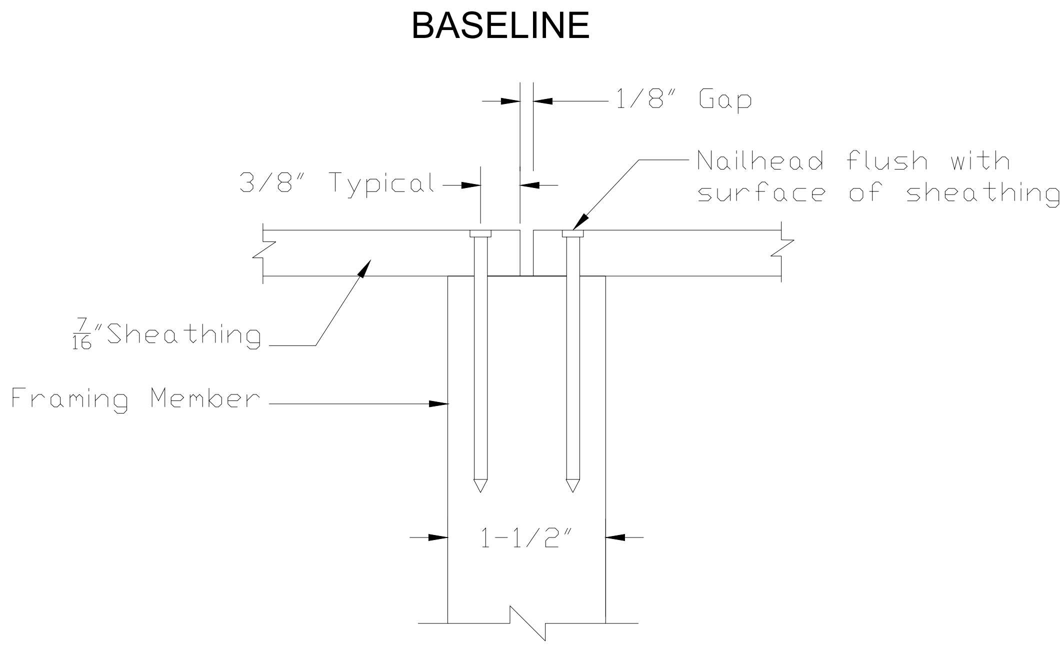


Figure 2.1 – Baseline Nailing

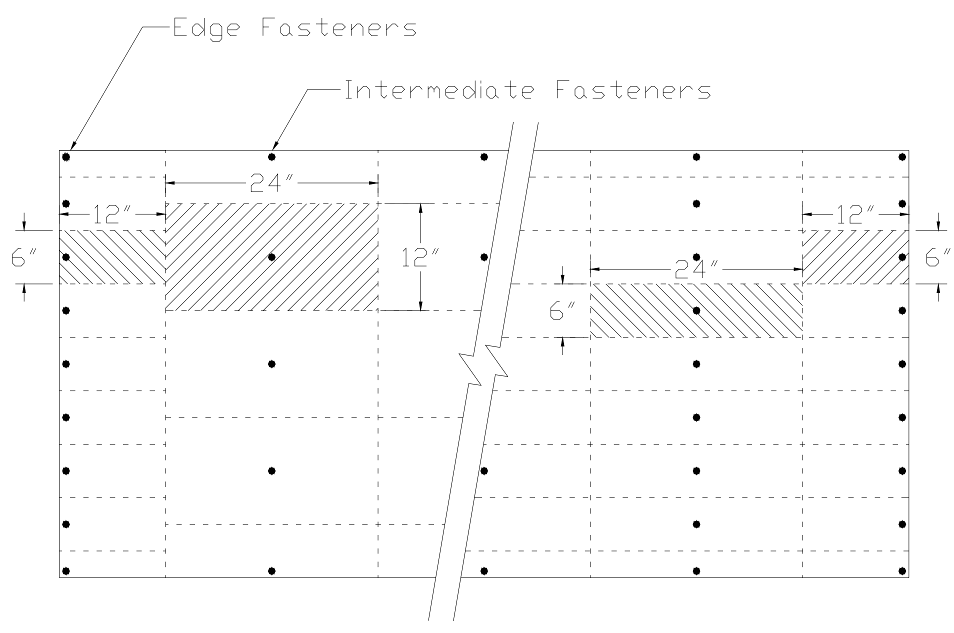


Figure 2.2 – Tributary loading areas for 12-inch and 6-inch nail spacing at intermediate supports

<u>Edge Distance</u>

Three variations in edge distance were tested: 1/8-inch, 1/4-inch, and 3/4-inch (see Figure 2.3). The 3/4-inch edge distance (Edge #3) required the edge-nail to be angled at approximately 20 degrees to keep the shank fully embedded in the framing member. A nail driven with a portion of its shank exposed from the underside was considered to be out of tolerance. All nails in this test program were kept within tolerance.

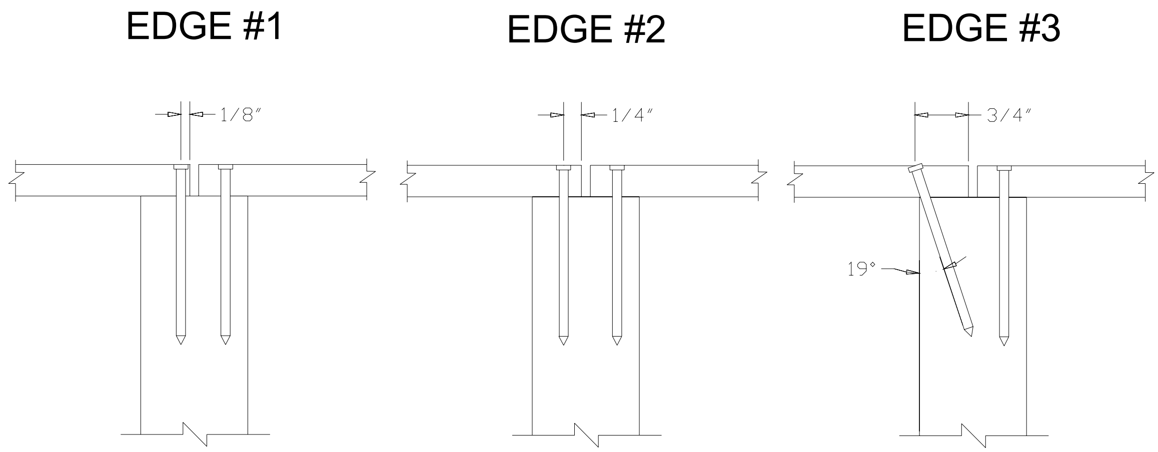


Figure 2.3 – Edge distance variations

Nail Spacing

Two variations in nail spacing were tested: one with the spacing increased by 1/2-inch, and the other with the spacing increased by 1-inch (see Figure 2.4). The number of fasteners (nine per intermediate support) along with the 3/8-inch edge distance requirement remained consistent with the baseline case. The varied spacing characteristic was applied on only one of the intermediate-framing members.

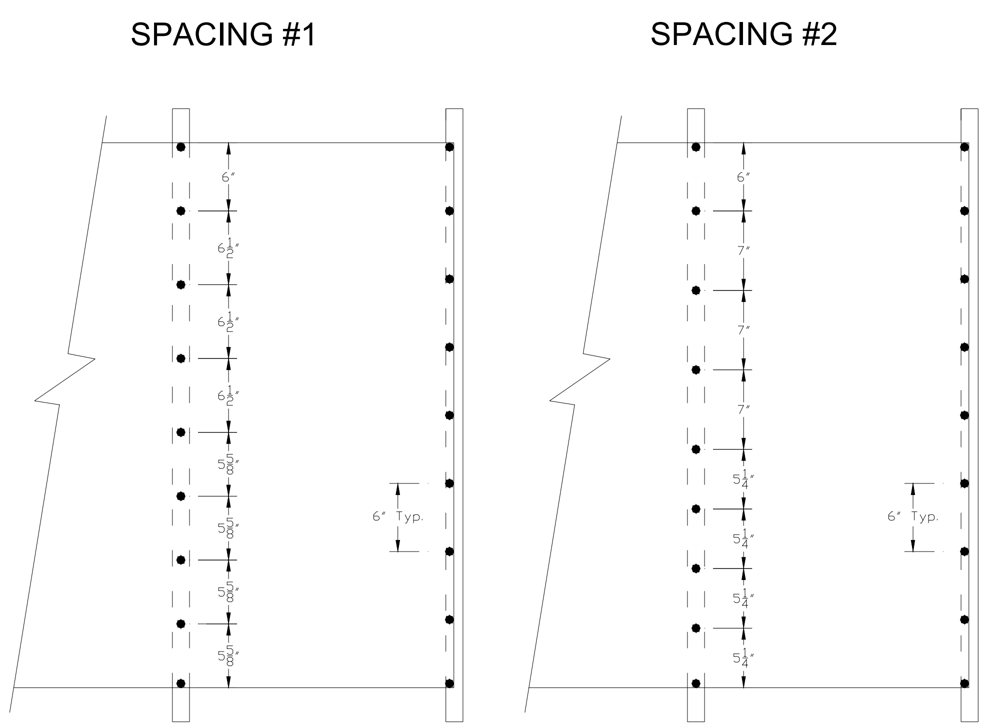


Figure 2.4 – Nail spacing variations

Nail Overdrive

Two variations were tested for nail overdrive: one up to 25 percent of the panel thickness, and the other up to 50 percent of the panel thickness (see Figure 2.5). The edge distance and spacing between fasteners were consistent with the baseline specifications. All fasteners for these tests were over-driven. However, precise and consistent over-drive was not achievable. Therefore, the actual penetration was measured after each nail had been installed. Tables 2.2 and 2.3 show the overdrive measurement data.

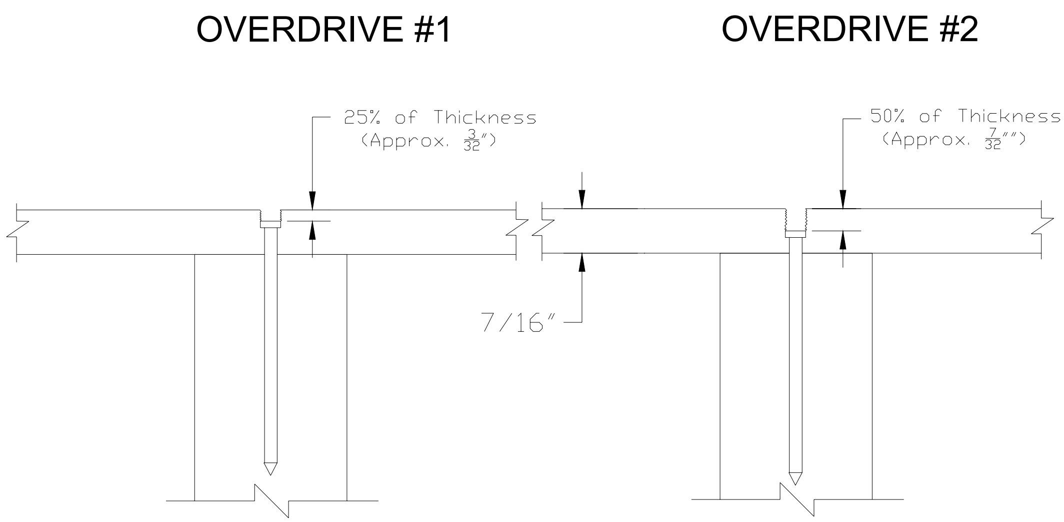


Figure 2.5 – Nail over-drive target variations

TABLE 2.2
ACTUAL NAIL OVERDRIVE DATA (Penetration #1)
(25% overdrive[1])

Test #	Maximum Overdrive (in)	Fastener Number at max.[2]	Minimum Overdrive (in)	Fastener Number at min.[2]	AVG Overdrive (in)	Std Dev (in)	COV	Initial Failed Fastener[2]	Overdrive at initial failure (in)
1	0.123	33	0.056	1	0.092	0.017	18%	15	0.101
2	0.178	15	0.065	1	0.101	0.026	26%	34	0.138
3	0.159	24	0.064	41	0.097	0.022	23%	29	0.104

[1]Target overdrive = 0.25 x 7/16-inch = 0.109 inches
[2]See Appendix A for fastener numbering and locations on test panel.

TABLE 2.3
ACTUAL NAIL OVERDRIVE DATA (Penetration #2)
(50% overdrive[1])

Test #	Maximum Overdrive (in)	Fastener Number at max.[2]	Minimum Overdrive (in)	Fastener Number at min.[2]	AVG Overdrive (in)	Std Dev (in)	COV	Initial Failed Fastener[2]	Overdrive at initial failure (in)
1	0.253	35	0.132	9	0.209	0.029	14%	16	0.198
2	0.266	35	0.142	38	0.204	0.030	15%	34	0.244
3	0.271	32	0.154	23	0.208	0.029	14%	31	0.271

[1]Target overdrive = 0.50 x 7/16-inch = 0.219 inches
[2]See Appendix A for fastener numbering and locations on test panel.

2.2 SHEATHING UPLIFT TESTS

Test Specimens

The sheathing uplift test specimens were framed with five 4-foot 6-inch long, nominal 2x6, Spruce-Pine-Fir (SPF), #1/#2 grade rafters, spaced 24 inches on center. One 4-foot by 8-foot sheet of 7/16-inch-thick, APA Span Rated 24/16, Exposure 1, OSB was fastened to the rafters with 8d common pneumatic-driven nails (0.131” x 2.5”), with full round heads in accordance with the variances established in the test matrix (Table 3.1). The rafters and sheathing were purchased from a local home improvement store and stored inside the NAHB Research Center laboratory for approximately three weeks prior to the construction of the specimens. The moisture content was measured at the time of construction and was found to be less than ten percent in all rafters. The specimens were tested within 48 hours after construction. After all testing was complete; the framing members were randomly sampled for specific gravity. The average specific gravity was 0.40, which is within four percent of the published specific gravity value (0.42) for SPF lumber [6].

All nails were installed with a pneumatic gun. For the overdrive tests, a special installation method for controlling the penetration depth was used. A weight was positioned on the back end of the gun to achieve the desired overdrive. Several trial installations were conducted with varying weights until the target penetration depth was achieved.

Test Apparatus

The uplift testing apparatus was designed to apply an equally distributed uplift pressure on the under-side of a sheathing panel. A steel frame, anchored to the floor was used to secure the ends of the rafters. An oversized, 8-mil plastic bag was placed in each of the four bays between the rafters and sheathing was attached to the framing to create four closed chambers containing the plastic bags. A foam insert was placed inside each bag to pre-form the bags to chambers. The plastic bags were attached to nozzles that protruded through the end of the steel frame. Each nozzle was connected to a polyvinyl chloride (PVC) pipe, which joined to a common PVC manifold. The manifold was connected to a variable pressure blower with a water manometer between the blower and the manifold (see Figures 2.6 and 2.7). The pressure in the system was monitored with the water manometer and controlled with manual valves on the blower.

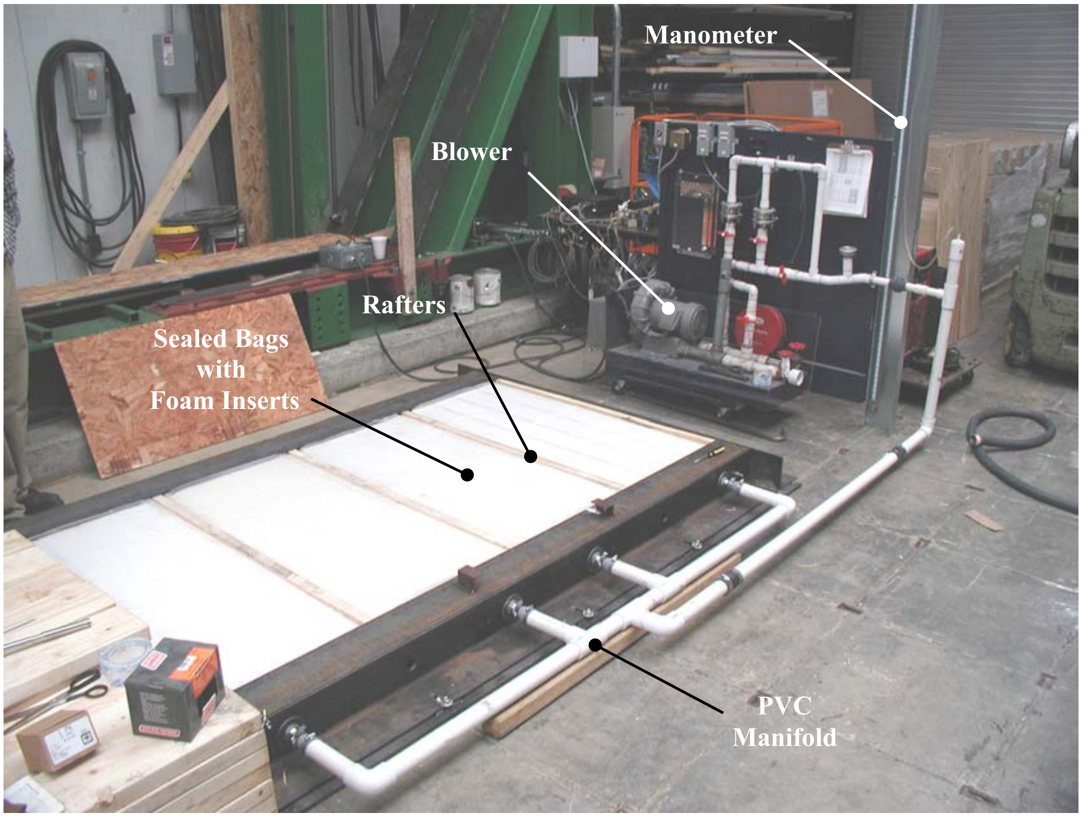


Figure 2.6 – Testing apparatus without sheathing

Figure 2.7 – Specimen setup with sheathing attached

Test Procedure

Pressure was applied to the specimen at an increase rate of 20 pounds per square foot per minute (20 psf/min), which was controlled by manually adjusting an intake valve on the blower while monitoring the water manometer. Two researchers observed the specimen as the pressure in the system was increased to record the location and mode of initial failure. The time between initial pressure application and specimen failure was approximately ten minutes. Failure was determined by a decrease in pressure by at least 50 percent of the observed ultimate pressure, or by a total loss of fastener connection at one or more locations. Failure modes included nail withdrawal from the framing, and the nail-head pulling through the sheathing panel. The maximum pressure was noted at the time of failure. The date, ambient temperature, relative humidity, and failure mode(s) were recorded for each tested specimen.

2.3 DIAPHRAGM SHEAR TESTS

Test Specimens

The diaphragm shear tests were conducted using partial roof diaphragms. These eight-foot by eight-foot diaphragm sections were tested in a vertical position with the framing members running horizontally. The bottom rafter was bolted to a rigid support and load was applied to the top rafter in a horizontal direction. The ends of the intermediate-framing members were restrained with blocking to prevent vertical displacement. The diaphragm sheathing was connected to the horizontal-framing members only, and not to the blocking or the vertical end members which supported the blocking. Steel straps were used to connect the ends of the rafters to the vertical end members and prevented the rafters from pulling out of the blocking.

The test specimens consisted of five, eight-foot, nominal 2x6, SPF #1/#2 grade, rafters, spaced 24 inches on center to create an 8-foot by 8-foot unblocked diaphragm frame. One 4-foot by 8-foot sheet, and two 4-foot by 4-foot sheets of 7/16-inch-thick, APA Span Rated 24/16, Exposure 1, OSB were fastened to the rafters with 8d common, full round head, pneumatic-driven nails (0.131” x 2.5”), in accordance with the variances established in the test matrix (Table 3.1). The rafters and sheathing were purchased from a local home improvement store and were stored inside the NAHB Research Center laboratory for approximately three weeks prior to the construction of the specimens. The moisture content was measured at the time of construction and was found to be less than ten percent in all rafters. The specimens were tested within 48 hours after construction. After all testing was complete; the framing members were randomly sampled for specific gravity. The average specific gravity was 0.40, which is within four percent of the published specific gravity value (0.42) for SPF lumber [6].

Test Apparatus

The diaphragms were tested in a shear racking device, which applied lateral load with a servo-controlled hydraulic ram (see Figure 2.8). The ram had a total travel range of 12 inches, and was connected to an eight-foot long, 1/4-inch-thick steel plate that was attached throughout to the top rafter with 1/2-inch diameter lag screws spaced 6 inches on center. Two sets of rollers were located at the top of the diaphragm frame to prevent out of plane movement. Four, 1/2-inch-diameter bolts, spaced approximately 30 inches on center, were used to attach the bottom rafter to the stationary test platform. A nominal 2x4 wood spacer was placed between the bottom rafter and the platform to allow for sheathing rotation. A hold-down bracket was attached to the left end-member to resist the overturning moment. An electronic load cell with a maximum capacity of 100,000 lb was used to measure the load.

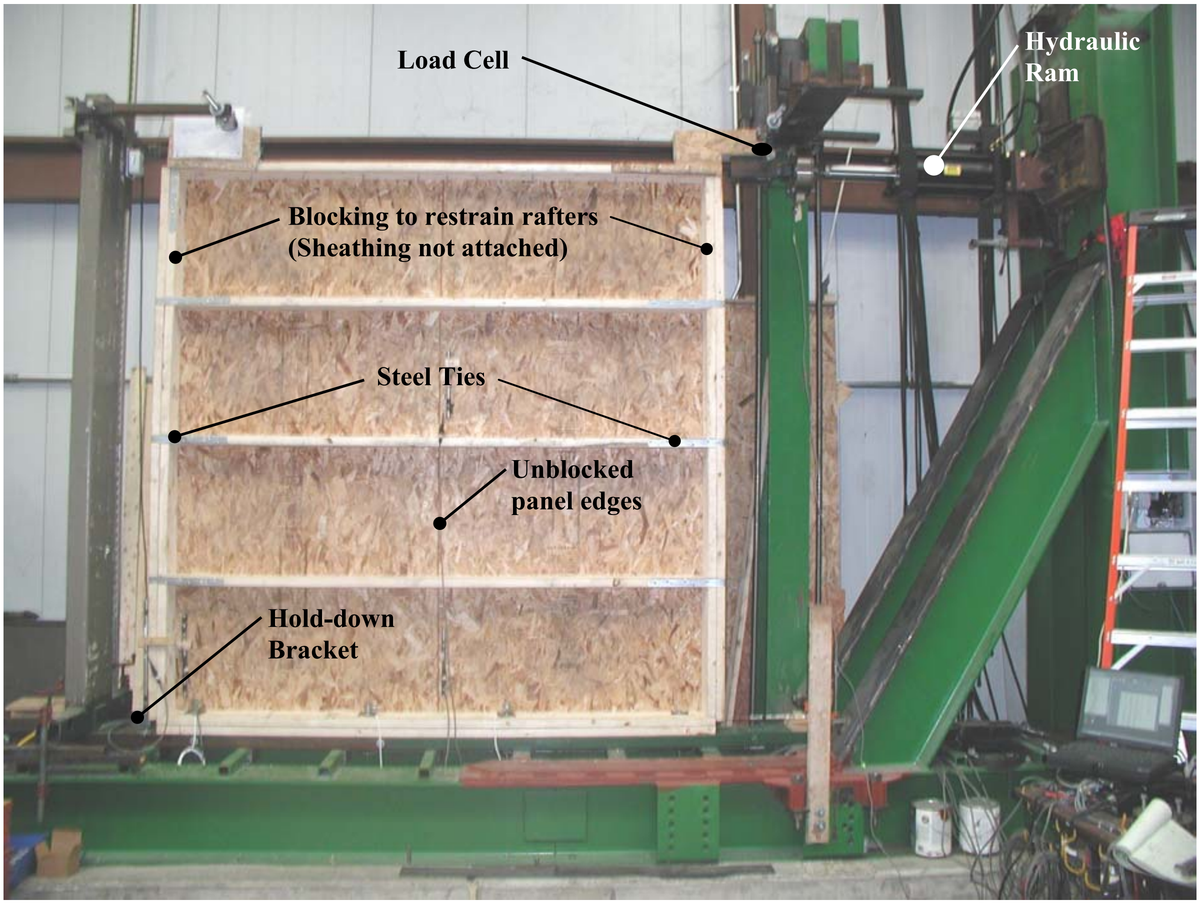


Figure 2.8 – Diaphragm specimen in shear racking apparatus

<u>Test Procedure</u>

Load was applied to the specimens by displacing the hydraulic ram at a constant rate of 0.3 inches per minute until failure. Failure was defined by a decrease in load by at least 25 percent of the observed ultimate load. Data was collected by a computer-based acquisition system [7]. The testing date, ambient temperature, relative humidity and failure modes were recorded for each specimen tested.

3.0 Test Results

3.1 Uplift Test Results

Twenty-three uplift tests were completed. Figure 3.1 shows the locations where the initial failures occurred. Nineteen of the specimens failed in Region A, one failed in Region B, and three failed in Region C. Five of the failures which started in Region A initiated at the second fastener from the end, ten initiated at the third fastener, and four at the fourth fastener. Two failure modes were observed: nail withdrawal and nail head pull-through. After the first nail began to fail, successive nail failures immediately followed, causing a complete specimen failure within five seconds. Table 3.1 is a summary of the uplift test results.

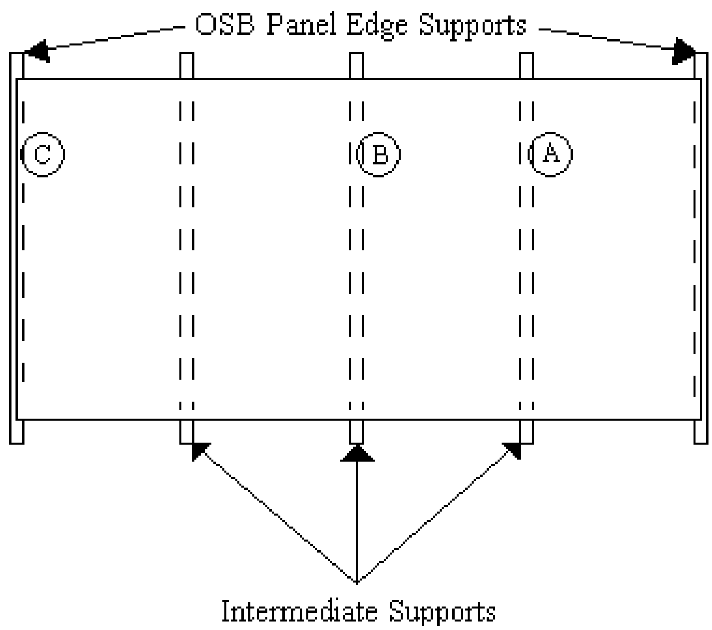


Figure 3.1 – Uplift failure locations (Regions A, B and C)

TABLE 3.1
UPLIFT TEST RESULTS

Test Number	Tested Characteristic	Ultimate Pressure (psf)	Average Pressure (psf)	Standard Deviation (psf)	COV	Initial Failure Location[1]	Failure Mode
1	Baseline	209	228	16	7 %	Region A	Pull Through
2		237				Region A	Withdrawal
3		237				Region A	Pull Through
4	Edge Distance #1 (1/8")	135	102	47	46 %	Region C	Pull Through
5		123				Region C	Pull Through
6		48				Region C	Pull Through
7	Edge Distance #2 (1/4")	236	248	16	7 %	Region A	Pull Through
8		259				Region A	Pull Through
9	Edge Distance #3 (3/4")	231	224	7	3 %	Region A	Withdrawal
10		225				Region A	Pull Through
11		216				Region A	Pull Through
12	Spacing #1 (6.5")	243	245	8	3 %	Region B	Withdrawal
13		237				Region A	Pull Through
14		253				Region A	Pull Through
15	Spacing #2 (7.0 inch)	193	211	20	10 %	Region A	Pull Through
16		233				Region A	Withdrawal
17		206				Region A	Pull Through
18	Overdrive #1 (25%)	212	182	29	16 %	Region A	Pull Through
19		154				Region A	Pull Through
20		181				Region A	Pull Through
21	Overdrive #2 (50%)	119	108	19	17 %	Region A	Pull Through
22		86				Region A	Pull Through
23		119				Region A	Pull Through

[1]See Figure 4.1 for region description.

Figures 3.2 and 3.3 show an uplift test in progress. Figure 3.2 shows the OSB deflecting just prior to failure, and Figure 3.3 shows the specimen immediately after failure.

Figure 3.2 – Specimen near ultimate load

Figure 3.3 – Specimen immediately after failure

3.2 CALCULATED UPLIFT CAPACITY

Calculated uplift capacities based on NDS [6] equations were compared to the capacities observed in the tests. The theoretical ultimate uplift pressure was determined using the calculated nail withdrawal strength and the assumed tributary loading area of the critical nail. The nail supporting the largest tributary loading area was assumed as the critical nail. The design withdrawal strength was calculated using Equation (1) [6], which is a function of the nail diameter and the specific gravity of the main member. The ultimate withdrawal capacity was determined with Equation 2, which applies a factor of five to the design strength [8]. The ultimate uplift load per nail was calculated with Equation 3, and the ultimate uplift pressure on the sheathing was then determined with Equation 4, by dividing the ultimate nail withdrawal value by the tributary area assigned to the critical nail.

$$W = 1380 G^{\frac{5}{2}} D \quad (1)$$

$$W_{ult} = 5 \times W \quad (2)$$

$$P_{ult} = W_{ult} L_p \quad (3)$$

$$\rho_{ult} = \frac{P_{ult}}{A_{trib}} \quad (4)$$

where:

W	= design nail withdrawal strength [6]
W_{ult}	= ultimate nail withdrawal strength (lb/inch of penetration) [8]
G	= specific gravity of main member (oven dry) [6]
D	= nail diameter (inches)
L_p	= nail penetration into main member (inches)
P_{ult}	= ultimate nail withdrawal force (lb)
A_{trib}	= tributary loading area for nail (ft^2)
P_{ult}	= ultimate uplift pressure for sheathing connection (psf)

For this test plan, the variables were:

G	= 0.40 (average specific gravity of tested lumber)
D	= 0.131 inches (8d common nail)
L	= 2.06 inches (nail length of 2.5 inches minus 7/16-inch sheathing thickness)
A_{trib}	= 0.94 ft^2 (tributary area for critical nail. See Appendix C)

$$W_{ult} = 5 \times 1380 \times (0.40^{\frac{5}{2}}) \times 0.131$$

$$W_{ult} = 91.5 \; {}^{lbs}\!/_{inch}$$

$$P_{ult} = 91.5 \times 2.06$$

$$P_{ult} = 188 \; lbs$$

$$\rho_{ult} = \frac{188}{0.94}$$

$$\rho_{ult} = 200\, psf$$

The calculated ultimate pressure underestimated the average tested ultimate pressure (200 psf calculated, verses 228 psf average tested) by 14 percent.

3.3 SHEAR TEST RESULTS

The partial diaphragms were designed to simulate the shear forces that occur in a full diaphragm. However, the partial diaphragms exaggerated weaknesses in edge nailing, and therefore were considered to provide conservative test results (i.e., ultimate test values were expected to be lower than ultimate values derived from code allowed design values).

Six diaphragm specimens were tested to failure (see Figure 3.4). Figure 3.5 shows the locations where the initial failures occurred. All six specimens initially failed at the bottom of the diaphragm (regions D and F), where the diaphragm was bolted to the rigid support. Overall, the diaphragms exhibited ductile type behavior, sustaining nearly 80 percent of the ultimate load at maximum displacement (approximately 8 inches). The initial failure for each of the specimens was nail tear-through at the panel edges (Figure 3.6 through 3.9). After the initial nail tear-through failure, some specimens exhibited rafter splitting (Figure 3.10). Table 3.2 is a summary of the shear test results.

Figure 3.4 – Diaphragm specimen under load

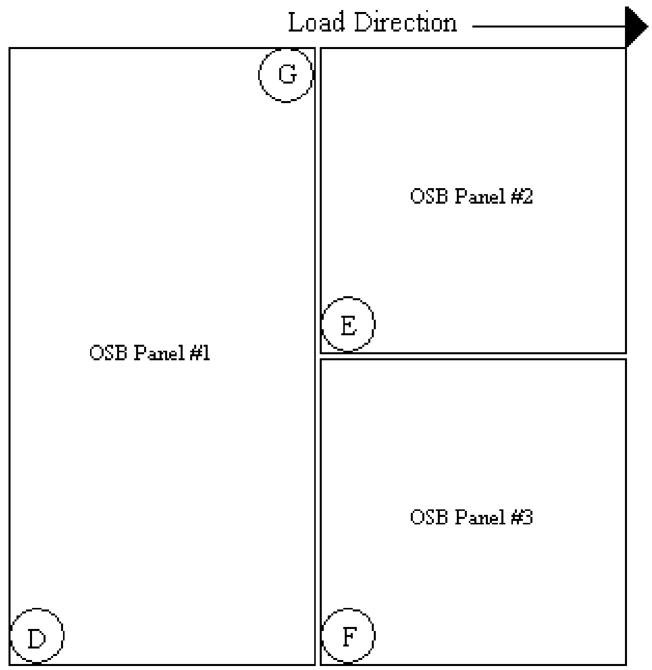


Figure 3.5 – Failure locations (Regions D,E,F, and G)

Figure 3.6 – Fastener tear-through failure at region D


Figure 3.7 – Fastener tear-through failure at region E


Figure 3.8 – Fastener tear-through failure at region F


Figure 3.9 – Fastener tear-through failure at region G

Figure 3.10 – Rafter splitting and tear-through

TABLE 3.2
SHEAR TEST RESULTS

Test Number	Tested Characteristic	Ultimate Load (lbs)	Average Load (lbs)	Standard Deviation (lbs)	Coefficient of Variance	Failure Mode
1	Baseline	2,494	2,575	115	4%	Tear-through
2		2,656				Tear-through
3	Overdrive #1	2,234	2,418	260	11%	Tear-through
4		2,602				Tear-through
5	Edge Distance #2	2,490	2,550	85	3%	Tear-through
6		2,610				Tear-through

4.0 Evaluation of Results

4.1 UPLIFT TESTS

The ultimate uplift capacities for the various nailing characteristics were compared with the baseline ultimate capacity. Table 4.1 shows the percent change in capacity from baseline for each of the nailing characteristics.

TABLE 4.1
CHANGE IN UPLIFT CAPACITY FOR TESTED NAILING CHARACTERISTICS

Tested Characteristic	Ultimate Uplift Pressure (psf)	COV	Percent Strength Loss (-) or Gain (+) from Baseline
Baseline	228	7 %	--
Edge Distance #1	102	46 %	- 55 %
Edge Distance #2	248	7 %	+ 9 %
Edge Distance #3	224	3 %	- 2 %
Spacing #1	245	3 %	+ 7 %
Spacing #2	211	10 %	- 7 %
Overdrive #1	182	16 %	- 20 %
Overdrive #2	108	17 %	- 53 %

4.2 SHEAR TESTS

The ultimate shear capacities for the tested nailing characteristics were compared with the baseline ultimate capacity. Table 4.2 shows the percent change in capacity from baseline for each of the tested characteristics.

TABLE 4.2
CHANGE IN SHEAR CAPACITY FOR TESTED NAILING CHARACTERISTICS

Tested Characteristic	Ultimate Load (lb)	COV	Percent Loss (-) or Gain (+) from Baseline
Baseline	2,575	5 %	--
Overdrive #1	2,418	11%	- 6 %
Edge Distance #2	2,550	3 %	- 1 %

The wind speed that would cause roof sheathing to blow off was assumed to be lower than the wind speed that would cause a roof diaphragm to fail in shear (i.e., sheathing will typically blow-off before a roof diaphragm fails in shear). Therefore, the major focus of this research was on uplift testing. The assumption that sheathing would blow-off first was analytically substantiated by back-calculating the diaphragm shear load that would occur at a wind speed high enough to blow off the sheathing. The average ultimate uplift pressure obtained in the *Baseline* tests served as the starting point for this calculation. A velocity pressure was determined using ASCE-7 [9], *Components and Cladding* (C&C) wind load equations and various building geometry assumptions (see Appendix B). The calculated velocity pressure was then used with ASCE-7, *Main Wind Force Resisting System* (MWFRS) equations to determine the diaphragm shear load at that wind speed. This calculated load represented the shear that would occur in a roof diaphragm when the wind speed was high enough to blow off the sheathing panels. This was compared with ultimate diaphragm shear values derived from appropriately adjusted diaphragm design values. Historically, diaphragm design values have incorporated safety factors in the range of 3.0 to nearly 6.0 [10]. Therefore, upper and lower bound diaphragm capacities were predicted by applying these factors, along with adjustments for lumber species and loading type, to the published design values:

Low   230 x 3.0 x 0.9 = 621 plf
High   230 x 6.0 x 0.9 = 1242 plf

- 1242: Expected shear capacity
- 0.9: Adjustment for SPF Lumber (S.G. = 0.42)[6]
- 6.0: Safety factor from APA tests [10]
- 230: Tabulated allowable diaphragm shear value (IBC-2003)[11]

This represents the loading range in which shear failure would be expected to occur. Table 4.2 shows the calculated diaphragm shear based on the velocity pressure associated with each of the uplift tests. In addition, the expected range for diaphragm shear capacity is included for comparison. In general, the calculated shear loads based on the ultimate uplift wind speeds are below, or at the lower end of the ultimate shear range. Therefore, it is reasonable to assume that roof sheathing will blow-off before the diaphragm will fail in shear. Consequently, for this test program, only nailing characteristics that had potential to cause large reductions in lateral capacity were tested in shear. These included panel edge spacing, and fastener overdrive.

TABLE 4.2
CALCULATED VELOCITY PRESSURE AND SHEAR LOADS

Tested Characteristic	Ultimate Uplift Pressure (psf)	Calculated Velocity Pressure (psf)	Calculated Shear Load (plf)	Published Diaphragm Shear Capacity[1] (plf)
Baseline	228	82	621	Range 621 to 1242
Edge Distance #1	102	37	278	
Edge Distance #2	224	81	611	
Edge Distance #3	248	89	677	
Spacing #1	245	88	668	
Spacing #2	211	76	576	
Overdrive #1	182	65	497	
Overdrive #2	108	39	295	

[1]Based on IBC (2003) design value of 230 plf for an unblocked diaphragm with 7/16-inch structural panels and 8d common nails. Base value is adjusted with 0.90 factor for SPF lumber, and a load factor varying from 3 to 6.

The partial diaphragm specimens performed closely to how full diaphragms would be expected to perform (i.e., ductile behavior). However, the partial diaphragms showed lower unit strengths. The capacity changes observed when the nailing variations were introduced were similar to those seen in the uplift tests. The changes were within the variability of the baseline tests and did not show unique responses to the altered nailing. Therefore, uplift was still considered to be the critical failure mode for any given wind pressure.

4.3 EDGE DISTANCE EFFECTS

Varying the edge distance did not affect the panel uplift connection capacity significantly until the edge distance was 1/8 inch. The 3/4-inch edge distance (Edge Distance #3) had an average capacity reduction of 3 percent, and the 1/4-inch edge distance (Edge #2) had a 9-percent increase in capacity. However, the initial connection failures for these tests occurred at intermediate framing members, where the edge spacing had not been altered. Therefore, the intermediate connections governed the uplift capacity and edge spacing from 1/4 inch to 3/4 inch could be considered acceptable without compromising strength. On the other hand, the 1/8-inch edge distance tests (Edge # 1) had initial failures on the panel edges. Large reductions in capacity were observed (over fifty percent) with this edge distance characteristic. Therefore, the 1/8-inch edge distance was interpreted as unacceptable. Moreover, this nail placement practice damaged the edge of the panel (see Figure 4.1). It was difficult to drive the nail with 1/8-inch edge distance without fracturing the edge of the panel.

For shear, nail tear through was consistently the mode of failure. At ¼-inch edge distance, the diaphragm shear tests showed only a 2-percent reduction in capacity. This was within the variability of the baseline shear tests of 5 percent. The larger edge distance characteristic (3/4 inch) was assumed to have negligible affects on the shear capacity due to the increased resistance to tear-through.

Figure 4.1 – Ineffective nailing for “Edge Distance #3”

4.4 NAIL SPACING EFFECTS

Varying the nail spacing did not significantly affect the uplift capacity of the sheathing connection. *Spacing #1* (nail spacing increased by 1/2 inch) had a seven percent increase in strength, and *Spacing #2* (nail spacing increased by 1 inch) had a seven percent decrease in strength when compared to the baseline tests. Since the capacity changes were within the variability of the baseline test results, the altered nail spacing was assumed to have no affect on the connection capacity and a one-inch tolerance for nail spacing could be established as a reasonable limit. The total number of nails per rafter would remain the same, but the placement accuracy could be relaxed to plus-or-minus one inch. Since the same number of nails will remain in each rafter, shear strength is assumed unchanged. Therefore, no shear tests were conducted for this nailing characteristic.

4.5 NAIL OVERDRIVE EFFECTS

The specimens with overdriven nails had significant reductions in capacity compared to the baseline tests. A near linear relationship between percent overdrive and percent capacity loss was observed (see Figure 4.2). Therefore, it was concluded that nail overdrive should be kept minimal, with a possible tolerance limits set at less than 10 percent. Although, if thicker than required sheathing were to be used, an overdrive that offsets the increased thickness may be acceptable.

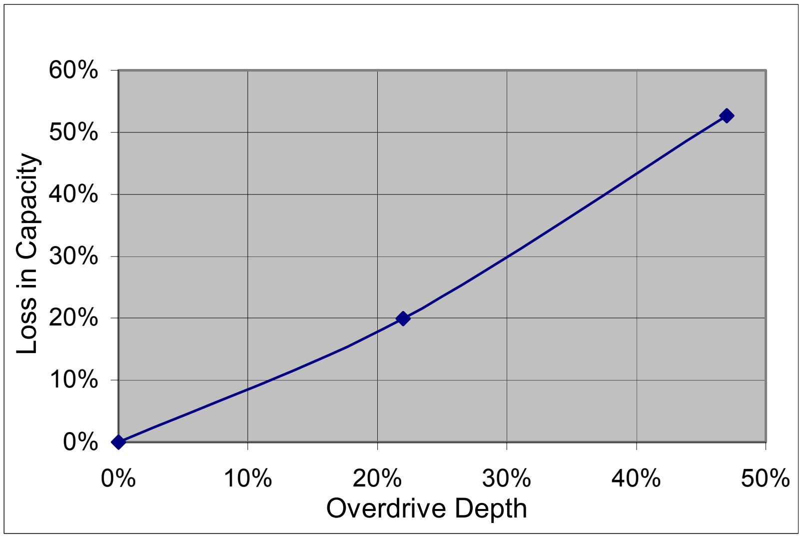


Figure 4.2 – Overdrive depth to capacity loss relationship

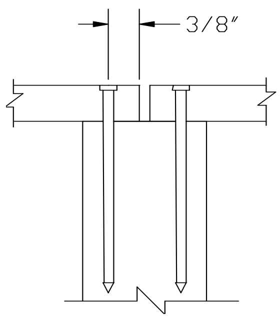
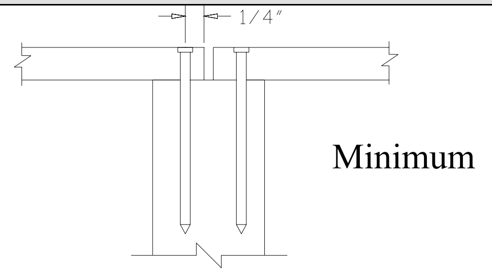
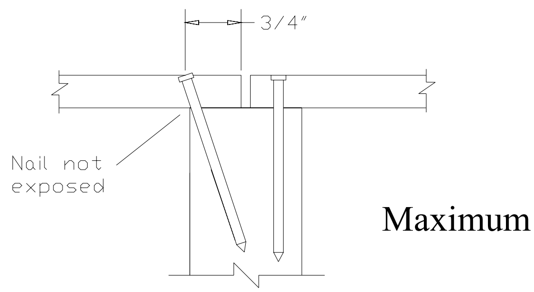
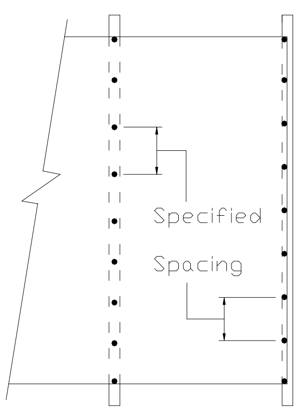
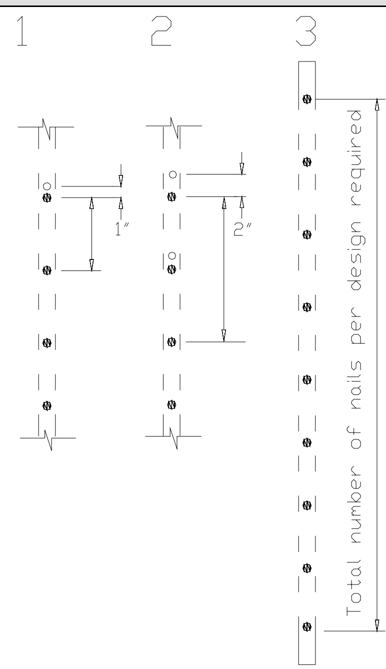
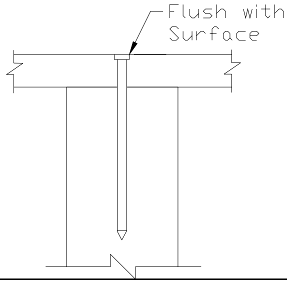
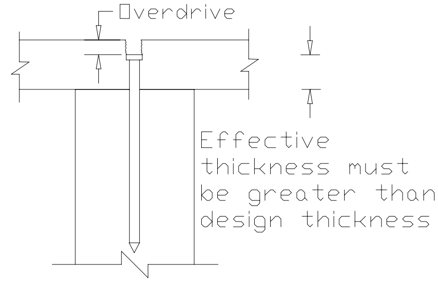
5.0 Conclusion and Recommendations

The results of this testing plan have shown that moderate variations in certain nailing characteristics have only minor affects on ultimate roof sheathing connection capacities. Tolerance limits for these nailing characteristics can be established with reasonable confidence using this test data. The implementation of these tolerance limits into installation specifications or quality-framing programs will enable builders to establish realistic framing goals and give building officials guidance as to what is acceptable and what is not.

The testing in this plan was limited to one type of sheathing and one nail type, but could provide insight into expected performance of other nail sizes. Nail diameters that exceed an 8d common diameter (0.131”) are likely to be more sensitive to closer edge spacing and may require tighter tolerances. Additional testing should be done if these nails are to be included in the tolerance limits.

Table 5.1 summarizes the recommendations for nailing tolerances for panel edge spacing, spacing between nails, and nail overdrive for 8d common nails or smaller and 7/16-inch thick OSB sheathing.

TABLE 5.1
SUGGESTED NAILING TOLERANCES

<table>
<tr><th>CURRENT GUIDELINES</th><th colspan="2">SUGGESTED TOLERANCES
(NAIL DIAMETER D ≤ 0.131” AND SHEATHING THICKNESS T ≥ 7/16”)</th></tr>
<tr><td colspan="3">Edge Distance:</td></tr>
<tr><td>3/8-inch from edge of panel to centerline of fastener
</td><td>Tolerance:
• Minimum = 1/4-inch from edge of panel to centerline of fastener
• Maximum = 3/4-inch from edge of panel to centerline of fastener and fastener angled such that no portion is exposed from the underside and the framing member remains un-split.</td><td>
</td></tr>
<tr><td colspan="3">Spacing Between Fasteners:</td></tr>
<tr><td>Spacing as specified (e.g., 6 inches on center)
</td><td>Tolerance:
1. Spacing between any two consecutive fasteners not to exceed specified spacing plus one inch.
and
2. Total distance between any three consecutive fasteners not to exceed minimum spacing multiplied by two, plus two inches.
and
3. Total number of fasteners in a nail line shall not be less than calculated using the minimum required spacing.</td><td></td></tr>
<tr><td colspan="3">Fastener Overdrive:</td></tr>
<tr><td>Head of fastener is to be driven flush with sheathing.
</td><td>Tolerance:
• Overdrive allowed if sheathing has been sized thicker than required by design. Depth of penetration must be kept such that remaining thickness under the head of the nail is greater than or equal to the required thickness but shall not exceed 1/3 the thickness of the panel.</td><td></td></tr>
</table>

6.0 References

[1] NAHB Research Center, Inc. 1993. Assessment of damage to single-family homes caused by hurricanes Andrew and Iniki. Prepared for the U.S. Department of Housing and Urban Development by the NAHB Research Center, Inc., Upper Marlboro, MD.

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[3] APA. 1999. *Proper Installation of APA Rated Sheathing for Roof Applications*. American Plywood Association.

[4] International Code Council (ICC), *International Residential Code 2003, (IRC 2003) for One- and Two-Family Dwellings*. ICC, Falls Church, VA

[5] APA. 1993. *APA Report T92-28: Roof Sheathing Fastening Schedules for Wind Uplift*. American Plywood Association, Tacoma, WA.

[6] AF & PA, National Design Specification for Wood Construction 1997 (NDS 97). American Forrest and Paper Association, Washington, DC

[7] IOtech, Inc. 1996. DaqView^{TM} v. 5.0. IOtech, Inc., Cleveland Ohio.

[8] AF & PA, Commentary on the National Design Specification for Wood Construction 1997. American Forrest and Paper Association, Washington, DC

[9] ASCE. 2000. *Minimum Design Loads for Buildings and Other Structures*. American Society of Civil Engineers, Reston, VA.

[10] APA. 1997. *APA Report 138: Plywood Diaphragms*. American Plywood Association, Tacoma, WA.

[11] International Code Council (ICC), *International Building Code 2003, (IBC 2003)*. ICC, Falls Church, VA

[12] NAHB Research Center. 2001. *Structural Design Loads for One- and Two-Family Dwellings*. National Association of Home Builders Research Center, Upper Marlboro, MD.

Appendix A
Panel Withdrawal Tests - Fastener Numbering

Figure A-1 shows the fastener numbering method used in the withdrawal tests to identify the location of each nail. Bold vertical lines represent the five rafters, and numbers identify the nails.

1	10	19	28	37
2	11	20	29	38
3	12	21	30	39
4	13	22	31	40
5	14	23	32	41
6	15	24	33	42
7	16	25	34	43
8	17	26	35	44
9	18	27	36	45

Figure A-1
Uplift testing numbering system

Appendix B
Estimated Wind Speeds and Diaphragm Shears

The following is an example calculation showing the method used to determine an equivalent wind speed and corresponding diaphragm shear load given an ultimate uplift pressure on a 4-ft. x 8-ft. roof sheathing panel.

Building Assumptions:

(1)	Enclosed Building		
(2)	Number of Stories	=	3
(3)	Length	=	50 feet
(4)	Width	=	25 feet
(5)	Roof Pitch	=	4:12 (Roof height = 4.2 feet)
(6)	Exposure	=	B
(7)	Story Height	=	10 feet
(9)	Uplift Failure Pressure	=	228 psf (Average ultimate uplift pressure from testing)
(10)	Roof Zone	=	3

Effective Component and Cladding Area (C & C Area) for individual nails spaced 6 inches on center with rafters spaced 24 inches on center:

2 ft x 0.5 ft = 1.0 ft^2

<u>Roof uplift</u>

Components and Cladding:

External Pressure Coefficient (GCp)	=	-2.6 (components and cladding zone 3)
Internal Pressure Coefficients (GCpi)	=	±0.18 (enclosed building)
Main Wind Force Resisting System		
Lateral Pressure Coefficient – Wall (GCp)	=	1.1 (Comb. windward and leeward walls)
Lateral Pressure Coefficient – Roof (GCp)	=	0.5 (Roof slope = 6:12 or less)
Topographic Factor (K_{zt})	=	1.0

Velocity Pressure

$q_h = p / (GC_p – GC_{pi}) = 228$ psf / [(-2.6) – (0.18)] = -82 psf

Velocity wind pressure is the same for the components and cladding and the main wind force-resisting system (a constant velocity pressure exposure coefficient is assumed for both loading conditions).

Design wind pressure for the main wind force resisting system

Walls: p = (82)(1.1) = 90 psf
Roof: p = (82)(0.5) = 41 psf

Diaphragm unit shear load (occurs at ultimate uplift capacity)

P = [(50)(5)(90)+(50)(4.2)(41)]/(2)/(25) = 622 lb/ft

Diaphragm unit shear capacity range

R_{Low} = (230)(0.9)(3.0) = 621 lb/ft
R_{High} = (230)(0.9)(6.0) = 1242 lb/ft

where:

230 lb/ft	= allowable tabulated diaphragm shear value (IBC-2003)
0.9	= adjustment factor for SPF with specific gravity of 0.40 (IBC-2003)
3.0	= ratio of capacity unit shear to allowable unit shear; this ratio was adopted as a minimum ratio from test data reported in APA Report 138.
6.0	= ratio of capacity unit shear to allowable unit shear; this ratio was adopted as the maximum ratio from test data reported in APA Report 138.

This comparison confirms that for the roof configurations investigated, uplift loading will typically govern the performance of roof sheathing connections (i.e., sheathing panel is expected to get blown off the rafters before the capacity of the roof diaphragm is exceeded).

Appendix C
Tributary Loading Areas for Nail Withdrawal

The total uplift pressure on a roof system is slightly higher than the uplift pressure that initiates nail withdrawal in the sheathing. This is because the uplift pressure exerted on the roof system is created by the pressure differential that occurs as air flows over the surface of the roof. The faster moving air on the outside surface of the roof creates a lower air pressure and therefore an upward force on the underside of the roof where higher air pressure remains (Figure C-1). The upward force is exerted on the entire underside of the roof system, including the underside of the rafters. A pressure differential does not occur between the rafter and the sheathing until withdrawal of the nail begins and a gap forms. Therefore, when calculating the tributary loading area for nail withdrawal (A_{trib}), the area where the rafter is in contact with the sheathing must be subtracted (Figure C-2).

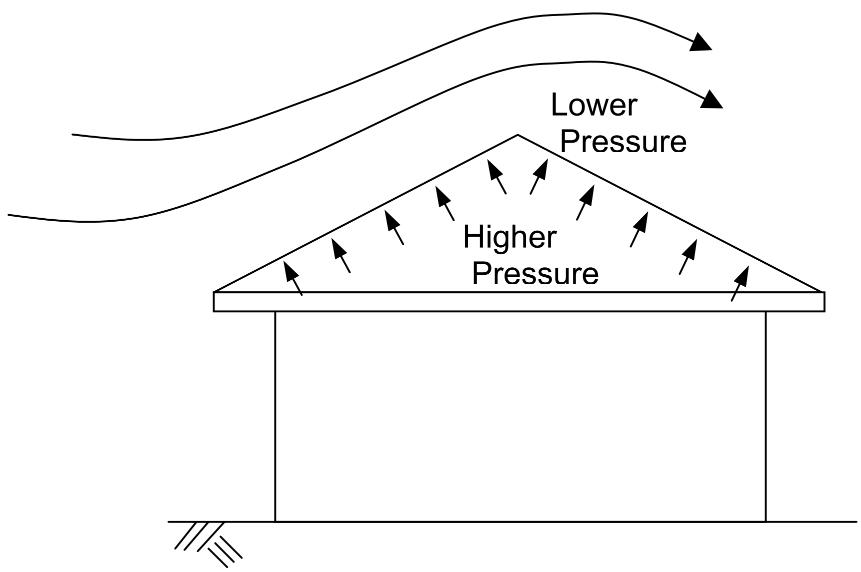

Figure C-1 – Pressure differential due to wind

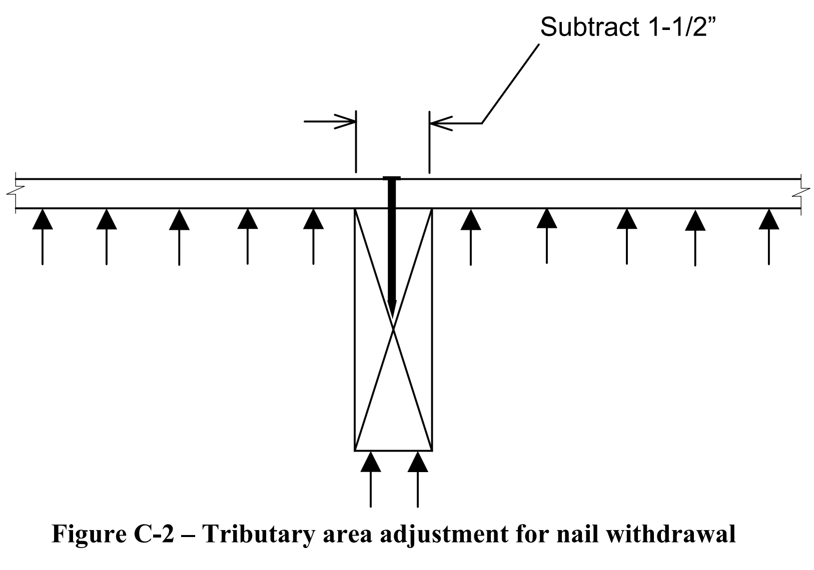

Figure C-2 – Tributary area adjustment for nail withdrawal

Appendix D
Metric Conversion Factors

The following list provides the conversion relationship between U.S. customary units and the International System (SI) units. A complete guide to the SI system and its use can be found in ASTM E 380, Metric Practice.

To convert from	to	multiply by
Length		
inch (in.)	micron (μ)	25,400
inch (in.)	centimeter	2.54
inch (in.)	meter (m)	0.0254
foot (ft)	meter (m)	0.3048
yard (yd)	meter (m)	0.9144
mile (mi)	kilometer (km)	1.6
Area		
square foot (sq ft)	square meter (sq m)	0.09290304
square inch (sq in)	square centimeter (sq cm)	6.452
square inch (sq in.)	square meter (sq m)	0.00064516
square yard (sq yd)	square meter (sq m)	0.8391274
square mile (sq mi)	square kilometer (sq km)	2.6
Volume		
cubic inch (cu in.)	cubic centimeter (cu cm)	16.387064
cubic inch (cu in.)	cubic meter (cu m)	0.00001639
cubic foot (cu ft)	cubic meter (cu m)	0.02831685
cubic yard (cu yd)	cubic meter (cu m)	0.7645549
gallon (gal) Can. liquid	liter	4.546
gallon (gal) Can. liquid	cubic meter (cu m)	0.004546
gallon (gal) U.S. liquid*	liter	3.7854118
gallon (gal) U.S. liquid	cubic meter (cu m)	0.00378541
fluid ounce (fl oz)	milliliters (ml)	29.57353
fluid ounce (fl oz)	cubic meter (cu m)	0.00002957
Force		
kip (1000 lb)	kilogram (kg)	453.6
kip (1000 lb)	Newton (N)	4,448.222
pound (lb)	kilogram (kg)	0.4535924
pound (lb)	Newton (N)	4.448222
Stress or pressure		
kip/sq inch (ksi)	megapascal (Mpa)	6.894757
kip/sq inch (ksi)	kilogram/square centimeter (kg/sq cm)	70.31
pound/sq inch (psi)	kilogram/square centimeter (kg/sq cm)	0.07031
pound/sq inch (psi)	pascal (Pa) **	6,894.757
pound/sq inch (psi)	megapascal (Mpa)	0.00689476
pound/sq foot (psf)	kilogram/square meter (kg/sq m)	4.8824
pound/sq foot (psf)	pascal (Pa)	47.88

To convert from	to	multiply by
Mass (weight)		
pound (lb) avoirdupois	kilogram (kg)	0.4535924
ton, 2000 lb	kilogram (kg)	907.1848
grain	kilogram (kg)	0.0000648
Mass (weight) per length)		
kip per linear foot (klf)	kilogram per meter (kg/m)	0.001488
pound per linear foot (plf)	kilogram per meter (kg/m)	1.488
Moment		
1 foot-pound (ft-lb)	Newton-meter (N-m)	1.356
Mass per volume (density)		
pound per cubic foot (pcf)	kilogram per cubic meter (kg/cu m)	16.01846
pound per cubic yard (lb/cu yd)	kilogram per cubic meter (kg/cu m)	0.5933
Velocity		
mile per hour (mph)	kilometer per hour (km/hr)	1.60934
mile per hour (mph)	kilometer per second (km/sec)	0.0268
Temperature		
degree Fahrenheit (°F)	degree Celsius (°C)	$t_C = (t_F-32)/1.8$
degree Fahrenheit (°F)	degree Kelvin (°K)	$t_K = (t_F + 459.7)/1.8$
degree Kelvin (°F)	degree Celsius (°C)	$t_C = (t_K -32)/1.8$

*One U.S. gallon equals 0.8327 Canadian gallon
**A pascal equals 1000 Newton per square meter.

The prefixes and symbols below are commonly used to form names and symbols of the decimal multiples and submultiples of the SI units.

Multiplication Factor	Prefix	Symbol
$1,000,000,000 = 10^{9}$	giga	G
$1,000,000 = 10^{6}$	mega	M
$1,000 = 10^{3}$	kilo	k
$0.01 = 10^{-2}$	centi	c
$0.001 = 10^{-3}$	milli	m
$0.000001 = 10^{-6}$	micro	μ
$0.000000001 = 10^{-9}$	nano	n