# Evaluation of Nailed Roof-to-Wall Connections for Resistance to Uplift

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# INTRODUCTION

In light-frame wood construction, nails have historically been the primary method for connecting roof members to walls. The connection, known as a toe-nail or a slant-nail, is fabricated by installing nails at an angle through the side of a roof framing members and into the wall's top plate. Model building codes allowed the use of toe-nails under conventional construction provisions in areas not prone to hurricanes. Recently, proposals to modify the conventional construction provisions to substantially reduce the applicability of toe-nailed connections have been discussed at various code development forums. This study is intended to provide the basis for establishing appropriate scoping limits for toe-nailed roof-to-wall connections in applications under the International Residential Code (IRC).

This testing program is designed to measure the uplift capacity of conventional light-frame roof connections. Testing is conducted on roof systems of rafters, rafters with ceiling joists, and trusses attached to the wall top plate using toe-nailed joints. The purpose of this study is to better understand how the roof-to-top plate connection performs as part of the roof system. Testing conducted by others (see Background) suggests that significant system effects are present when connections are tested as part of a roof assembly as compared to values for individual nails or individual connections predicted by engineering analysis or evaluated by testing. The system response provides potential for load sharing between individual connections, particularly connections with variability in resistance. Specific objectives of this study are to:

1) measure the uplift resistance of roof systems attached using toe-nail schedules per IRC RB207-07/08[1];
2) measure the uplift resistance of roof systems attached using alternative toe-nail schedules; and,
3) measure the uplift resistance of a roof system attached using ring-shank nails to evaluate the upper bound capacity of toe-nailed joints.

# BACKGROUND

This section summarizes results of selected research efforts on roof uplift connections that are relevant to the objectives this study.

**J.A. Sholten and E. G. Molander (1950)**

The research done by Sholten and Molander investigated several types of stud to plate connections in both lateral and tensile loading. The tested connections included toe-nailed connections using two 8d, 10d or 16d common wire nails through the wide face of the stud (one nail through each side), end-nailed connections using two 8d, 10d, 16d or 20d common wire nails and strap/plate connections using metal U-strap, L-strap or gusset plates installed with 8d common nails. All assemblies were constructed using 2x4 Douglas Fir members. Testing also investigated the effect of lumber moisture content on the strength of the connection by testing each connection type under three different conditions: first when the connection was fabricated with dry lumber and tested dry, second using wet lumber during fabrication and allowing it to dry before testing, and third using wet lumber for fabrication and immediately testing the wet assembly.

[1] International Code Council (ICC), 2007/2008 Code Development Cycle, Volume 2, 2008 Final Action Agenda, RB207-07/08 with Public Comments, ICC, Country Club Hills, IL.

Testing was conducted by applying load either laterally or in tension to the stud section at a constant rate of 0.0125 inches per minute.

Results of lateral testing showed that connections using metal U-straps achieved the greatest ultimate capacity at 1,450 lb. Of the two conventional type connections tested, the four 8d toe-nails out performed even the two 20d end nails, showing ultimate loads of 872 lb and 839 lb respectively. Results of testing in tension showed that the metal U-strap connection achieved an ultimate capacity of 2,308 lb. Of the conventional connections, the end-nailed assemblies performed weakest, achieving ultimate loads of 310 lb, 211 lb and 518 lb with two 10d nails, two 16d nails and two 20d nails, respectively. The toe-nailed connections performed much better with ultimate loads of 452 lb, 816 lb and 871 lb for four 8d nails, four 10d nails and four 16d nails, respectively. The typical failure mode seen in the tension tests of the toe-nailed connection was withdrawal of the nails from the plate.

Overall, although increased separation occurred in connections that were assembled using green wood and then allowed to dry before testing, the ultimate loads were comparable to those built and tested using dry lumber.

**T.D. Reed, D.V. Rosowsky and S.D. Schiff (1997)**
Testing by Reed et al. investigated the uplift capacity of various rafter-to-top plate connections using realistic test specimens to simulate as-built conditions. Several different rafter-to-top plate connection configurations were tested including three 8d common (2.5” x 0.131”) toe-nails individually and in combination with various hold down straps and adhesives. Toe-nails were installed through both sides of the rafter, two on one side and one on the opposite side. Rafters were fitted to the top plate using the typical practice of a “bird’s mouth” cut. Test specimens were constructed using Southern Yellow Pine 2 x 4 top plates and either Southern Yellow Pine or Spruce-Pine-Fir 2 x 6 rafters. All lumber was #2 or better in grade.  It should be noted that after review of data with the authors of the report, another study (NAHB Research Center, 1999) suggested that spruce-pine-fir (SPF) lumber was used, not Southern Yellow Pine.

Testing was done on a single rafter-to-top plate connection. Results for specimens connected using three toe-nails yielded an average ultimate strength of 430 lb. The typical failure mode exhibited was nail withdrawal from the top plate. Results for connections using both toe-nails and various size metal hold down straps ranged between 1,640 lb and 3,220 lb, depending upon size and number of straps used. The typical failure modes for these tests were nail withdrawal, as well as tearing of the straps.

A second set of testing was done on a series of connections to evaluate the system effects of an as-built roof system. Test specimens consisted of seven rafter-to-top plate connections spaced at 16 inches on center and sheathed on the top using 1/2-inch-thick OSB. The rafters were allowed to pivot about their ridge ends by use of a steel pipe threaded through the ends of the rafters. The specimens were loaded using either a spreader beam or a uniform load tree. Results showed increases in the equivalent single rafter loads over the individual connection capacities found in the first set of tests. An ultimate equivalent rafter load was 670 lb for the system tests, compared to an average ultimate load of 430 lb for a single connection. This difference in capacity provided evidence for the authors to suggest that load sharing behavior occurs in the typical roof system. The authors also noted that differing load capacities for the same specimen configuration were found when the two different loading methods were used. They suggested that further testing be done to determine the “correct loading mechanism” to imitate actual wind loading, presumably somewhere between the equal loading of the load tree and the equal displacement of the spreader beam.

The results of this testing were also used to determine appropriate safety factors or allowable design capacities for the various connections. It was noted that strap manufacturers used a safety factor of 3.0. However, the authors suggested using the $5^{th}$ percentile values to align with the LRFD procedures being used at the time. Also the 3.0 factor of safety was thought to be excessively conservative given the low coefficient of variation seen in the test data.

**Robinett (2003)**
The testing done by Robinett examined the uplift capacity of roof rafter- or truss-to-top plate connections in existing homes for both the original as-built connections and after various retrofits were installed. The as-built connections tested consisted of three or four 16d common toe-nails between the rafter and the top plate, H2.5 Simpson hold down straps in combination with the 16d common toe-nailed connection, both with and without diagonal wall strapping, and H2.5 Simpson hold down straps with toe-nailing and metal strapping between each stud and the top and bottom plates of the wall. The different retrofits included adding H10 or H2.5 hold down straps by Simpson, installing 1/2-inch-thick plywood sheathing, metal strapping and anchor bolts, and adding a “Sutt Bracket” which is a steel angle lag bolted to both the roof rafters or trusses and the wall studs.

Testing was conducted on sections of the existing roof system consisting of either four or eight rafters or trusses, spaced at 24 inches on center. Load was imposed using a crane and loading tree which was attached to each rafter or truss. The loading tree allowed each rafter or truss to displace individually while applying a consistent load. Load was measured using 5,000 pound load cells located at each rafter/truss. Each section of roof was separated from the rest of the roof system by a series of cuts along the direction of the rafters or trusses and extending from one edge of the roof to the other. The exterior walls were not separated from the rest of the house.

Results for the rafter or truss connected to the top plate using only three or four toe-nails ranged between 635 lb and 762 lb. Typical failure modes included withdrawal of the nails and splitting of the rafters. When H2.5 Simpson straps were used in addition to toe-nailing, results ranged from 800 lb up to 1,900 lb depending on how far the strapping extended down through the structure. The uplift capacity increased as the strapping was taken farther down towards the foundation. The typical failure mode for these connections was withdrawal of the nails attaching the strap to the lower top plate and failure of the upper top plate. Testing of the different retrofits yielded uplift capacities ranging between 876 lb and 3,952 lb, with the greatest capacities occurring when strapping was added to extend the load path down further towards the foundation.

**Cheng (2004)**
The objective of the testing by Cheng was to evaluate the uplift capacity of individual roof rafter-to-top plate toe-nailed connections.

Testing was done on ten different toe-nailed connection configurations that included the following variables: three 8d common or box nails, two 16d common or box, two 2.5-inch screws, 2 x 4 or 2 x 6 lumber sizes, spruce-pine-fir or Southern Yellow Pine or Douglas Fir lumber, and installation techniques with or without pilot hole. Testing was done in accordance with ASTM D 1761.

Results of the testing showed the average ultimate load for a connection using 8d box nails into 2x4 SPF lumber and installed with a pilot hole was 248 lb, which was very similar to the ultimate load of 255 lb seen for a hand driven 16d box nail with the same lumber. An ultimate load of 350 lb was seen for the same size 16d box nail installed with a pilot hole into a 2x6 SPF. An actual decrease in ultimate capacity was seen when the same connection was tested with lumber of a higher specific gravity, 332 lb with lumber having a specific gravity of 0.45 compared to 350 lb for the lumber with an specific gravity of 0.42. Connections into Douglas Fir lumber using 16d box nails achieved ultimate capacities between 584 lb and 637 lb. In every test using SPF lumber, the exhibited failure mode was nail withdrawal. For the Douglas Fir and Southern Yellow Pine, some failures of the rafter member were observed. For a toe-nailed connection using screws the average ultimate load was 861 lb with the typical failure mode of tearing of the wood. The authors used a factor of safety of 2.5 applied to the average ultimate load for comparison to calculated design wind loads.

## METHODS AND MATERIALS

Specimens were fabricated and tested at the NAHB Research Center Laboratory facility located in Upper Marlboro, Maryland. Testing was conducted during the summer of 2008. Lumber, trusses, fasteners, gypsum board, and OSB panels were purchased from local suppliers. Table 1 summarizes the test matrix with details specific to each test. A sample size of two was used for each roof system.

**Table 1 – Test Matrix**

| Roof System | Spacing | Connection & Nail Description[1,2] | Description | Number of tests |
|---|---|---|---|---|
| Conventional Rafter (2x6's, SPF #2) | 16" o.c. | 3 - 16d box (3.5" x 0.131") | 2 nails on one side and 1 nail on the opposite side | 2 |
| Conventional Rafter/Ceiling Joist (2x6's, SPF #2) | 16" o.c. | Joist to top plate 3 - 8d box (2.5" x 0.113") Rafter to top plate: 2 - 16d box (3.5" x 0.131") | Joist: 2 nails on open side and 1 on rafter side<br><br>Rafter: both nails on open side | 2 |
| | | Joist to top plate 2 - 16d box (3.5" x 0.131") Rafter to top plate: 2 - 16d box (3.5" x 0.131") | Joist: 1 on open side and 1 on rafter side<br><br>Rafter: both nails on open side | 2 |
| | | Joist to top plate 2 - 16d box ring shank (3.5" x 0.131") Rafter to top plate: 2 - 16d box ring shank (3.5" x 0.131") | Joist: 1 nail on open side and 1 nail on rafter side<br><br>Rafter: 2 nails on open side | 2 |
| Metal Plate Connected (MPC) Wood Truss | 24" o.c. | 3 - 16d box (3.5" x 0.131") | 2 nails on one side and 1 nail on the opposite side. 2 nails installed through the truss plate – 1 on each side. | 2 |

1. All nails are for pneumatic installation. Nail sizes are per manufacturer's specification. Actual nail sizes were also measured and were consistent with the nominal values except that the diameter of 16d nails was 0.128". Nominal sizes were used for calculations of allowable design values in Table 2. Pneumatic nails with diameter of 0.135" (i.e., nominal diameter for 16d box nails) were not readily available at the time of testing.
2. All nails are smooth shank unless otherwise noted. Coating was chemically removed from all smooth-shank nails.

Figures 1, 2, and 3 show the test setup for the three specimen configurations; conventional rafters only, conventional rafters with ceiling joists and metal plate connected (MPC) wood trusses, respectively. The roof specimens were 8 feet wide (in the direction perpendicular to framing members) by 10 feet long (horizontally in the direction parallel to framing members) with a 12-inch overhang. For the specimens with rafters spaced at 16 inches on center, this resulted in a total of 6 roof-to-plate connections tested as part of one assembly. For the specimens using trusses spaced at 24 inches on center, this resulted in a total of 4 roof-to-plate connections tested as part of one assembly. The specimens were framed such that the first connection occurred at the distance equal to half the roof member spacing from the edge of the specimen. This allowed for equal loading on all connections. Blocking was provided for the sheathing at the specimen edges. This practice is consistent with ICC-ES procedures for testing assemblies with multiple sheathed members (ICC-ES AC-86, 2008).

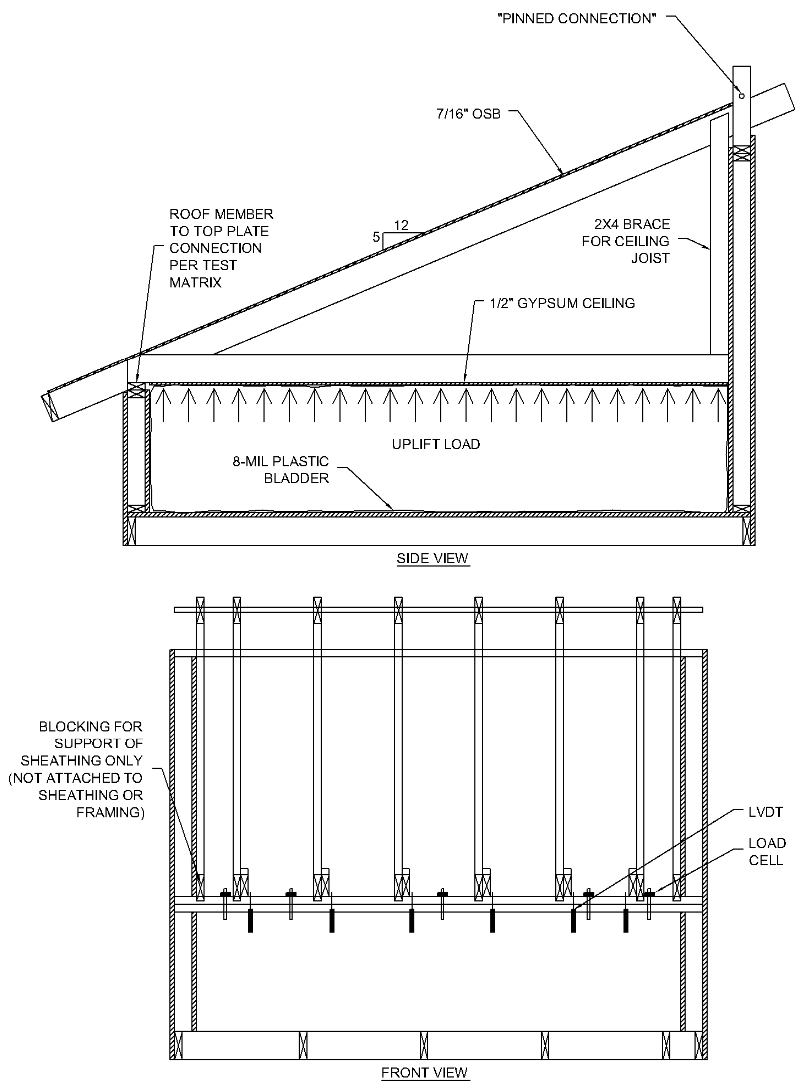


**Figure 1 – Uplift set-up of specimen with ceiling joists**

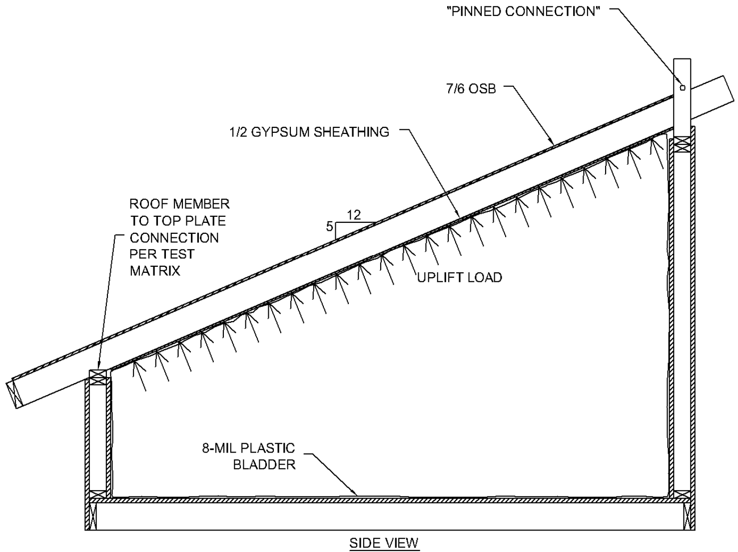


**Figure 2 – Uplift set-up of specimen without ceiling joists**

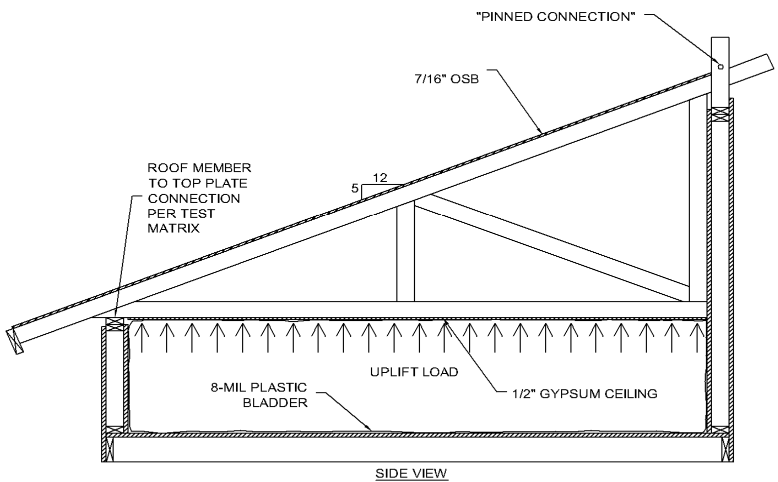


**Figure 3 – Uplift set-up of specimen with MPC roof trusses**

Figures 4 and 5 show photos of the test setup. The specimens were subjected to a uniform uplift load applied using a pressurized 8-mil polyethylene bladder. The bladder was placed inside a structurally reinforced test box and the specimens were placed on top of the box to simulate typical roof conditions. The box was built using wood framing sheathed on both the interior and exterior faces with 7/8-inch-thick OSB.

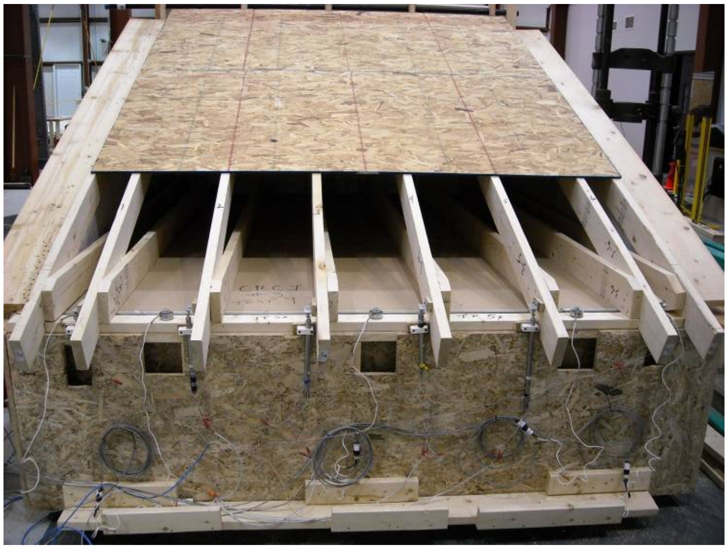

**Figure 4 – Uplift set-up instrumentation (OSB panel is not attached to show connections and instrumentation)**

**Figure 5 – Uplift specimen ready for testing**

The smooth-shank pneumatic nails used in the roof-to-plate connections were manufactured by Senco and the ring-shank pneumatic nails were manufactured by Paslode (Figure 6). The smooth-shank nails had a symmetric full round head. The ring-shank nails had an asymmetric full round head (Figure 7). Because the IRC allows the use of smooth-shank common nails without coatings, all pneumatic smooth-shank nails were chemically cleaned of any adhesive prior to testing. The toe-nails were installed using a pneumatic nail gun at an angle approximately between 35 and 40 degrees off vertical and with the head of the nail located approximately 1/3 of the total nail length from the top plate (Figures 8 and 9). The location of the nail head is in accordance with the requirements of Section 11.1.5.4 of the National Design Specification for Wood Construction (NDS, 2006). The angle was slightly greater than 30 degrees recommended by the NDS because the weight and configuration of the nail gun made it difficult to position it at a 30-degree angle. It should be noted that some of the framing members did split during installation of the toe-nails. However, splitting to the extent shown in Figure 10 typically occurred in no more than one framing member per specimen.


**Figure 6 – Pneumatic nails used in roof-to-plate connections**

**Figure 7 – Asymmetrical full round head of Paslode 16d ring-shank nails**


**Figure 8 – Installation of toe-nails**

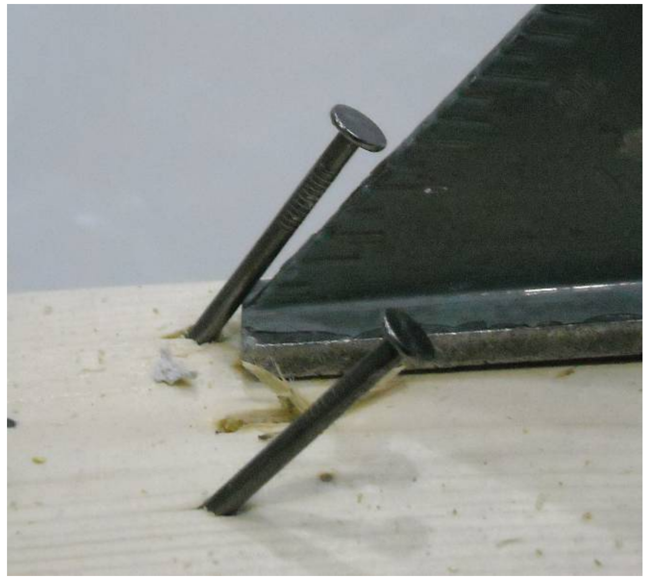

**Figure 9 – Angle of installed toe-nails (Toe-nails after pull-through failure)**

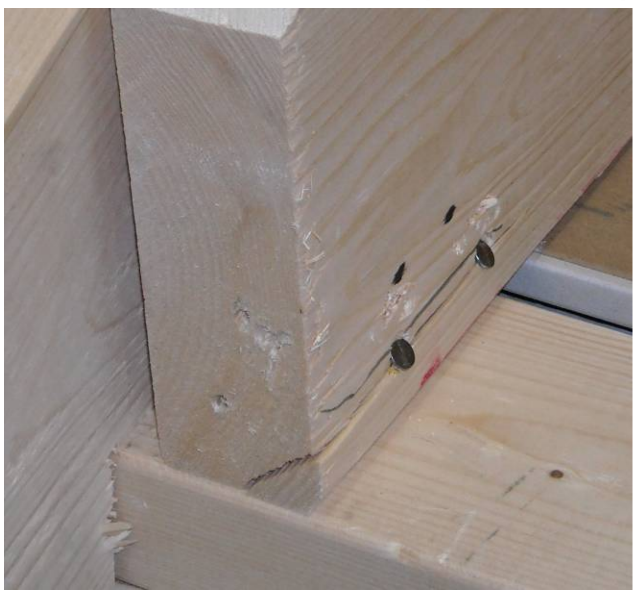

**Figure 10 – Splitting of ceiling joist during installation of toe-nails**

The rafters were constructed at a 5:12 pitch and notched to bear on the top plate of a wall using a "bird's mouth" cut. The end of the rafters (or truss top chords) were tied together using either a 2 x 8 or 1 x 6 fascia board end nailed to each member with two 8d common (2.5" x 0.131") nails. The 1 x 6 fascia board was used with the rafter/ceiling joist specimens with the four 16d box joints and four 16d ring shank joints, and for the roof truss specimens. The 2 x 8 fascia was used with all other configurations. There was no difference observed in the response of the two fascia boards. Where ceiling joists were present, each joist was attached to the adjacent rafter using three 10d pneumatic (3" x 0.120") nails. 7/16-inch-thick OSB was installed as roof sheathing and attached using 8d common (2.5" x 0.131") nails spaced at 6 inches on center around the panel perimeter and 12 inches on center in the field of the panel. 1/2-inch-thick gypsum wallboard was installed as interior ceiling covering using 1-5/8 inch Type W drywall screws spaced at 12 inches on center. Where no ceiling joists were present, the gypsum wall board was installed directly to the interior face of the rafters, as is in cathedral or vaulted ceiling construction. All rafters and ceiling joists were 2 x 6 Spruce-Pine-Fir (SPF) #2 grade lumber. The wall top plates were 2 x 4 Spruce-Pine-Fir (SPF) #2 grade lumber. The MPC trusses were purchased pre-fabricated using 2 x 4 Southern Yellow Pine lumber.

Moisture content of the top plates and roof framing members during fabrication and testing ranged from 8 to 12%. Average specific gravity of the roof framing members was 0.39. Because specific gravity of the main member is an important property in the performance evaluation of toe-nails, specific gravity of each top plate was measured before testing to avoid lumber with specific gravity substantially higher than the published value (SG = 0.42 for SPF, per NDS). Specific gravity of top plates used in testing ranged between 0.40 and 0.43.

Testing was conducted using a pressurized box system controlled via computer software. Instrument readings including load and deflection measurements were recorded using a computer based data acquisition system. Loading was applied at a rate such that ultimate load was achieved in not less than 5 minutes.

The roof assembly specimens were attached to the top member of the double top plate per the test matrix (Table 1). The bottom member of the double top plate was attached to the test box structure. The two members of the double top plate were tied together using five 1/2-inch bolts. There were no other attachments between the top plates. The top member of the double top plate was replaced after each test. The opposite end of the specimens was restrained from uplift by a 1-1/4 inch diameter steel pipe attached to the test apparatus. This allowed the specimen to pivot and isolate the uplift failure at the top plate connection. Where ceiling joists were present, a vertical 2 x 4 member was provided between the rafters and joists at the pinned end.

Load was measured using five electronic load cells located at each bolt. The load cells were placed on top of the double top plate to capture the load transferred from the roof assembly connections to the top double plate. The nuts on the bolts were finger tightened to less than 10 pounds at the beginning of each test to avoid any pretension on the bolts, yet still provide contact between the washers and the load cells such that there was no slack at the joint. Deflections were measured at each of the connections using Linear Variable Differential Transformers (LVDT).

# RESULTS

***General***

Table 2 provides a summary of the test results and comparison to allowable design values.

The specimens failed in a manner that the entire roof system separated from the double top plate, i.e., it was a system failure rather than failure of individual connections (Figure 11). Load per connection was calculated by summing the load cell forces across the length of the top plate and dividing by the number of connections. It should be noted that peak loads for different load cells occurred at different times indicating a load redistribution mechanism between stronger and weaker connections. The maximum capacity of the system was taken as the highest total force resisted by the system (not the summation of the individual peak loads for each load cell).

The allowable design values are calculated in accordance with the NDS for SPF lumber with specific gravity of 0.42. The allowable design values are calculated for the normal load duration conditions ($C_D$=1.0 based on live load) and for the 10-minute load duration ($C_D$=1.6 based on wind load). Both allowable design values are compared to the test values. The allowable design values for normal load duration conditions are provided to allow direct comparison of the “tested-to-allowable” ratio to the safety margins expected per the NDS. In accordance with the NDS commentary (Commentary NDS, 1997), the normal duration allowable design values represent about one-fifth of the average ultimate test values for withdrawal or toe-nailed connections. The allowable design values for wind loading are provided for evaluation of safety margins relative to design wind forces. As an example, the intended safety margin for wind loading for nailed connections loaded in shear is about 2.0.

RB207 references a 200 lb trigger for toe-nailed connections with three 16d box nails, two on one side of the connection and one on the other side. This trigger assumes that the toe-nail factor does not need to be applied to roof-to-wall connections. Therefore, Table 2 also provides comparison to design values which do not include the toe-nail factor adjustment.


**Figure 11 – Specimen after failure**

**Table 2 – Test Results**

| Roof System | Nail/Connection Type | Total Uplift Load | Average Test Load per Connection [1] | Allowable design value (normal duration) [2] | Tested/ Allowable (normal duration) | Allowable design value (wind load) [3] | Tested/ Allowable (wind load) | Allowable design value w/o toenail reduction (wind load) [4] | Tested/ Allowable w/o toe-nail reduction (wind load) |
|---|---|---|---|---|---|---|---|---|---|
| | | (lbs) | (lbs) | (lbs) | | (lbs) | | (lbs) | |
| **Conventional Rafters @ 16" oc** | 3 - 16d box (3.5" x 0.131") | 4,297<br>4,222 | 710 | 89 | 8.0 | 142 | 5.0 | 212 | 3.3 |
| **Conventional Rafter w/ Ceiling Joist @ 16" oc** | Joist: 3 - 8d box (2.5" x 0.113") Rafter: 2 - 16d box (3.5 x 0.131") | 4,129<br>4,019 | 679 | 115 | 5.9 | 184 | 3.7 | 275 | 2.5 |
| | 4 - 16d box (3.5" x 0.131") (Rafter 2 nails and joist 2 nails) | 4,638<br>4,852 | 791 | 119 | 6.6 | 190 | 4.2 | 284 | 2.8 |
| | 4 - 16d box Ring Shank (3.5" x 0.131") (Rafter 2 nails and joist 2 nails) | 5,375<br>4,804 | 849 | 119[5] | 7.1 | 190[5] | 4.5 | 284[5] | 3.0 |
| **MPC Wood Trusses @ 24" oc** | 3 - 16d box (3.5" x 0.131") | 2,802<br>2,566 | 671 | 89 | 7.5 | 142 | 4.7 | 212 | 3.2 |

1. Load per connection is calculated by dividing the total uplift load by the number of connections, i.e., by 6 for 16" on center and by 4 for 24" on center spacing.
2. Allowable design value for normal duration ($C_D$=1.0), includes a toe-nail factor adjustment ($C_{tn}$=0.67). SG=0.42 is used.
3. Allowable design value for wind loading based on 10 minute duration ($C_D$=1.6), includes a toe-nail factor adjustment ($C_{tn}$=0.67). SG=0.42 is used.
4. Allowable design value for wind loading based on 10 minute duration ($C_D$=1.6), does not include toe-nail factor adjustment ($C_{tn}$=1.0). SG=0.42 is used.
5. Design value for smooth-shank nails is used for comparative purposes only. NDS does not provide an increase for ring-shank nails.

***Conventional Rafters***

Rafters were attached to the top plate using three 16d pneumatic box nails in accordance with RB207. The average capacity was 710 lb per connection. Figures 12 and 13 show typical failure modes including nail withdrawal from the top plate, pulling through the rafter, and rafter splitting. The predominant failure mode was nail withdrawal from the top plate. It is interesting to note that compared to specimens with a ceiling joist, rafter-to-wall connections are subject to both uplift and thrust forces. There was no evidence of reduction in capacity due to such loading. In fact, there is a potential for improved friction between the nail and the wood due to the force normal to the body of the nail.

**Figure 12 – Nail withdrawal and rafter splitting**

**Figure 13 – Nail after pulling through rafter**

***Conventional Rafters with Joists***

The first configuration under this group is in accordance with the fastening schedule of RB207: three 8d box nails in the joist and two16d box nails in the rafter. Figure 14 shows a typical failure mode that included withdrawal of 8d nails along with pull-through of 16d nails and splitting of the rafters. Although the total number of nails increased compared to the conventional rafter-only connection, the average capacity of this connection was 679 lb – a 4.4% reduction. This result indicates that 8d box nails do not have sufficient penetration into the top plate to develop comparable performance as 16d box nails even if normalized by length and diameter. As evidence, the safety margin relative to the allowable design values is reduced and is the lowest among all other tested connections that do not contain 8d nails (Table 2).

Another consideration in the comparison between the performance of 8d and 16 nails is the effect of the length of the nail point on the total penetration into the main member. The length of the point does not contribute to the nail's withdrawal performance. Therefore, the effective nail length is less than its total length. However, the NDS uses the total nail length for the purposes of engineering calculations. The relative effect of the point length is greater on the penetration depth of shorter nails (8d) than longer nails (16d).

**Figure 14 – Nail withdrawal of the 8d nails and pull through of 16d nails**

In the second configuration under this group, the joists were attached to the top plate with two 16d box nails in lieu of three 8d box nails. Therefore, a total of four 16d nails were used per joint: two per rafter and two per joist. The intent for this configuration is to provide an alternative connection that uses a single nail type to allow for simplified construction. The typical failure mode for this configuration was a combination of withdrawal from the top plate along with pull-through and splitting of the roof member (Figures 15 & 16). The average connection capacity increased to 791 lb. The safety margins compared to the allowable design values have also increased. Although the total depth of penetration of three 8d box nails is greater than the total depth of penetration of two 16d box nails (4.6 inches for three 8d box vs. 4.3 inches for two 16d box), the total connection capacity using four 16d nails is 16% higher. This observation confirms the trend observed in the previous configuration that 8d box nails are less effective in toe-nail applications than 16d box.

**Figure 15 – Nail withdrawal and pull-through failure modes of 16d nails**

**Figure 16 – 16d nails in plate after pull-through failure**

The third configuration under this group included testing of ring-shank nails. The intent of this configuration is to establish an upper bound capacity for toe-nailed connections. A total of four 16d box ring-shank nails were used to allow direct comparison with the previous configuration. The average capacity was 848 lb per connection, a 7.3% increase from the 16d box smooth shank results. The typical failure mode was associated with nails pulling through the roof members (Figures 17 & 18). Therefore, the limiting factor for the performance of ring-shank toe-nails is the capacity of the wood framing, capping the total connection's capacity at below 900 lb (the first test of this configuration reached 896 lb per connection). As previously noted, the ring-shank nails had an asymmetric round head configuration. It is possible that a different type of nail head can improve the pull-through performance.

**Figure 17 – Pull-through failure of all ring-shank nails**

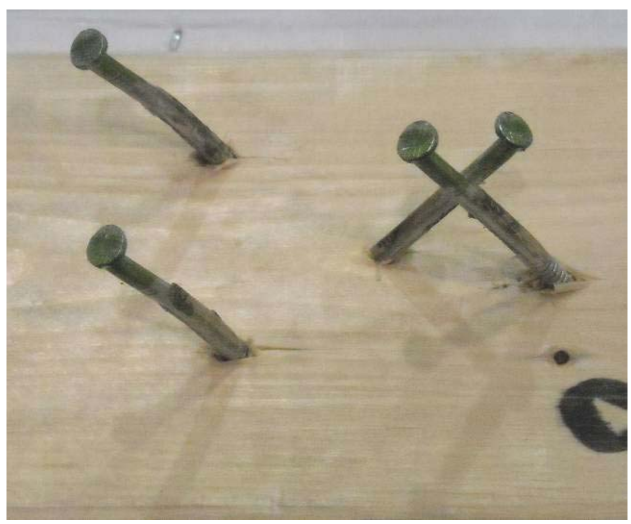

**Figure 18 – Ring-shank nails after pull-through failure**

***Metal Plate Connected Wood Trusses***

One connection configuration of a MPC wood truss roof was tested using three 16d box nails in accordance with RB207. Because this connection is affected by the location of the truss plate relative to wood framing, the truss heel joint was selected such that the location and size of the truss plate allowed for two nails be driven through the truss and one nail directly through the wood (Figure 19). This configuration allowed to capture the effect of a nail located near the end grain of the beveled edge, which has a potential propensity to splitting. Figure 20 shows the typical failure mode that included withdrawal of the nails from the top plate. The metal truss plates reinforced the wood of the bottom chord minimizing the potential for wood splitting and eliminating the nail pull-through failure mode. Even where local splitting of the bottom chord occurred near the nail installed at the beveled edge, the truss plate was effective at keeping the wood member together such that all nails withdrew from the top plate. The capacity of the truss-to-roof connection was 671 lb per joint, a 5.5% reduction relative to a three16d box nail connection for conventional rafters. However, the performance of the two configurations is considered equivalent, as this reduction can be attributed primarily to the increased framing spacing of 24 inches on center. This increased spacing contributed to reduced stiffness of the boundary conditions at the edge trusses due to the increased width of the free edge (12 inches for trussed spaced at 24 inches on center vs. 8 inches for framing spaced at 16 inches on center). In a complete roof assembly, the sheathing is either continuous or attached to boundary members, resulting in increased boundary stiffness.

**Figure 19 – Installation of one nail through the truss plate and one nail adjacent to the truss plate**

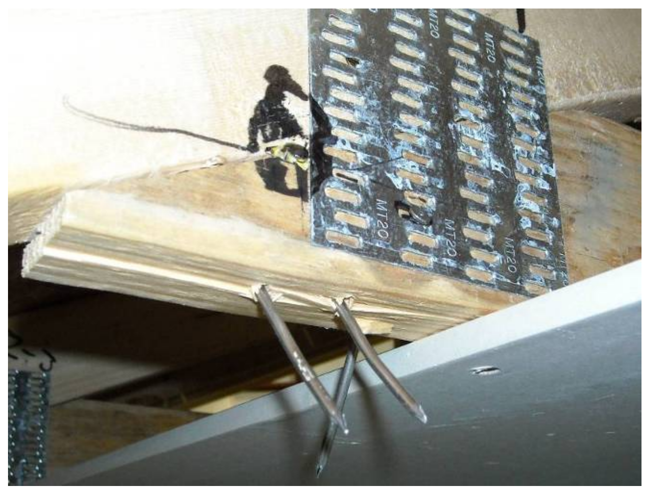


**Figure 20 – Nail withdrawal failure mode for truss configuration**

***Other Observations***

Where the primary failure mode was withdrawal of the nails from the top plate, the wood around the nail was subject to crushing and tearing to allow for withdrawal of an angled nail to occur (Figure 21). This response mode should also in part explain the improved performance of 16d nails vs. 8d nails – the longer nails have an increased horizontal projection engaging more wood to resist tearing. This toe-nail response is different from a straight nail pullout where the resistance is controlled only by the friction between the nail and the wood fibers.

**Figure 21 – Local tearing/crushing of top plate associated with withdrawal failure mode**

As discussed previously in the Methods section, the nails were generally installed at an angle ranging approximately between 35 and 40 degrees. This installation practice reduced the penetration depth by 4% to 8%. However, all calculations of design values for the purpose of comparing to test values were performed for a 30-degree angle. Although this is a conservative approach, it allowed for direct comparisons to design specifications and to tabulated values. Moreover, the increased angle has a potential to trigger a nail bending mechanism in lieu of direct nail withdrawal.

The system effects present in the tested wall assemblies are attributed to load sharing between individual connections through the resistance provided by sheathing materials and the fascia board. The system response forced all nails to fail nearly at the same time.

In other studies that tested individual nails or joints, there is a potential for the roof member movement at an angle due to asymmetric nailing pattern (one nail on one side and two nails on the opposite side) or due to variability of performance of individual nails (local density variability, different angle, wood splitting at one of the nails, etc). Testing of a roof system with multiple joints ensures that the movement occurs in true vertical direction further contributing to load sharing, minimizing potential for local failures at weaker joints.  This also forces the body of the nail to tear the wood of the main member to enable the nail pull-out in lieu of a straight withdrawal.

***Safety Margins***

All configurations substantially exceeded the expected safety margins between the tested and the design values.

The ratio of the tested capacity to the allowable value for normal load duration ranged between 5.9 and 8.0 (first shaded column in Table 2), exceeding the expected average margin of 5.0.

The ratio of the tested capacity to the allowable value for wind loading ranged from 3.7 to 5.0 (second shaded column in Table 2), exceeding the expected minimum margin of 2.0.

The last ratio (third shaded column in Table 2) represents a safety margin of the tested values relative to the design values without the penalty of the toe-nail factor. This comparison is relevant in context of RB207 where the toe-nail factor was set to unity ($C_{tn}$=1.0) for applications with the IRC. This ratio ranged from 2.5 to 3.3 confirming that the toe-nail factor does not need to apply to the system performance of roof-to-wall connections.

The smallest margins were observed for the configuration with 8d box nails attaching the ceiling joist. As previously discussed, it appears that a reduced penetration of 8d box nails into the main member is the reason for the reduced safety margins. If the configuration with 8d box nails is excluded from consideration, the margins for all other configurations are reasonably consistent – the ratio without the toe-nail factor (third shaded column) ranges from 2.8 to 3.3. If a safety margin of 2.5 is used for connections with three or four smooth-shank 16d box nails, the upper bound of conventional toe-nailed connections ranges between 268 lb and 316 lb, respectively.

## SUMMARY AND CONCLUSIONS

This testing program is designed to measure the system performance of conventional roof-to-wall toe-nailed connections under uniform uplift load. The results of the study are intended to provide the basis for establishing appropriate scoping limits for toe-nailed roof-to-wall connections in applications under the International Residential Code (IRC). A summary of specific observations, conclusions, and recommendations is provided below:

1. The system response of the specimen resulted in load sharing between individual joints such that the failure was associated with a simultaneous or a near simultaneous degradation of all connections, i.e., specimens failed as a system.
2. The primary failure mode for smooth-shank toe-nails was withdrawal from the top plate with some nails pulling through the roof framing. The primary failure mode for ring-shank toe-nails was pull-through the roof framing. In trusses, the metal plates reinforced the bottom chords such that nails always withdrew from the top plate.
3. The safety margins for all configurations were higher than expected based on the NDS calculations. As one outcome, the applicability of the toe-nail reduction factor may need to be reevaluated for roof-to-wall systems under uplift loading.
4. The lowest safety margin was observed for connections that included 8d box nails. Therefore, 16d box nails that provide an increased penetration depth into the main member are more effective in toe-nail applications.
5. If a safety margin relative to capacity is set at 2.5, the resistance of toe-nailed connections with three or four smooth-shank 16d box nails ranges between 268 lb and 316 lb, respectively.
6. By testing ring-shank nails with improved withdrawal resistance, the tested upper bound capacity for toe-nailed connections, as limited by nails pulling through the roof members, is estimated at below 900 lb per connection.

## REFERENCES

American Forest & Paper Association. 2005. *National Design Specification for Wood Construction.* American Wood Council, Washington, DC.

American Forest & Paper Association. 1997. *Commentary National Design Specification for Wood Construction.* American Wood Council, Washington, DC.

ICC Evaluation Services, Inc (ICC-ES). 2008. *Acceptance Criteria for Cold-Formed Steel Framing Members – Interior Non-Load Bearing Wall Assemblies (AC-86).* ICC-ES, Whittier, CA.

International Code Council (ICC), 2007/2008. *Code Development Cycle, Volume 2, 2008 Final Action Agenda for the Proposed Changes to the 2006 Edition of the International Residential Code, RB207-07/08 with Public Comments*. ICC, Country Club Hills, IL.

International Code Council (ICC). 2006. *International Residential Code for One and Two-Family Dwellings.* ICC, Country Club Hills, IL.

NAHB Research Center. 1999. Reliability of Conventional Residential Construction: An Assessment of Roof Component Performance in Hurricane Andrew and Typical Wind Regions of the United States. Prepared for the U.S. Department of Housing and Urban Development and the National Association of Home Builders. NAHB Research Center, Upper Marlboro, Inc., MD.

Scholten, J., and Molander, E. 1950. *Strength of Nailed Joints in Frame Walls*. Agricultural Engineering.

Reed, T., Rosowski, D. and Schiff, S. 1997. *Uplift Capacity of Light-Frame Rafter to Top Plate Connections*. Journal of Architectural Engineering, Reston, VA.

Robinett, D. 2003. *Assessment of Retrofits for High Wind Resistance.* College of Engineering, Clemson University, Clemson, SC.

Cheng, J. 2004. *Testing and Analysis of the Toe-nailed Connection in the Residential Roof-to-Wall System.* State Farm Insurance Companies, Bloomington, IL.