connection failure modes (i.e., wood splitting and tear-out) that preceded more ductile failure modes associated with the yield theory.

4. Use of light-gage steel hurricane clips doubled the shear transfer capacity of the system to about 560 lb/joint (Table 16) without use of blocking between the trusses.

5. The resistances of toe-nails and hurricane clips can not be superimposed due to different stiffness characteristics of two connection types (Table 16).

6. Because metal truss plates limit the area available for installation of toe-nails (Figure 16) and the beveled end of ceiling joist is susceptible to premature splitting (Figure 17), the toe-nailed truss-to-wall connection is not necessarily equivalent to conventional roof-to-wall connections that use roof systems assembled with rafters and joists rather than trusses. Therefore, further research is needed to develop prescriptive connection requirements for MPC trusses consistent with the use of three 8d common toe-nails with conventional roof systems.

7. Using capacity as the design basis, the lateral allowable resistance of hurricane clip H2.5 in the direction parallel to wall can be doubled relative to the values provided by the clip manufacturer.

8. In moderate- to high-hazard areas of the United States, use of simple roof ties without additional blocking or detailing can significantly improve the shear transfer through roof diaphragm systems into shear walls in conventional residential construction and engineered wood-frame construction.

4.3 TASK 3 – INDIVIDUAL ROOF-TO-WALL TOE-NAILED CONNECTION TESTS

4.3.1 Objective

The objectives of Task 3 were to measure the performance of individual toe-nailed roof-to-wall connections and to evaluate the engineering design methodologies for analysis of toe-nailed connections. Common and pneumatic nails were investigated. The differences in the lateral response between toe-nailed and face-nailed connections and the limitations of the yield theory application to toe-nailed connections were identified. Moreover, potential system effects were investigated through comparison of the results of full-scale (Task 2, Section 4.2) and individual connection tests.

4.3.2 Experimental Approach

A series of tests on individual roof-to-wall connections with the nailing schedules adopted from the full-scale testing (Section 4.2) was conducted. Two connections (Table 18) corresponding to specimen configurations 1 and 2 of the full-scale tests (Table 14) were investigated. Figure 23 shows the test setup.

TABLE 18
SPECIMEN CONFIGURATIONS FOR INDIVIDUAL ROOF-TO-WALL CONNECTION TESTS

CONFIGURATION	CONNECTION[1]	SAMPLE SIZE	CORRESPONDING CONFIGURATION FROM FULL-SCALE TESTS (TABLE 13)
1	2-16d pneumatic nails (toe-nailed)	10	1
2	3-8d common nails (toe-nailed)	10	2

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

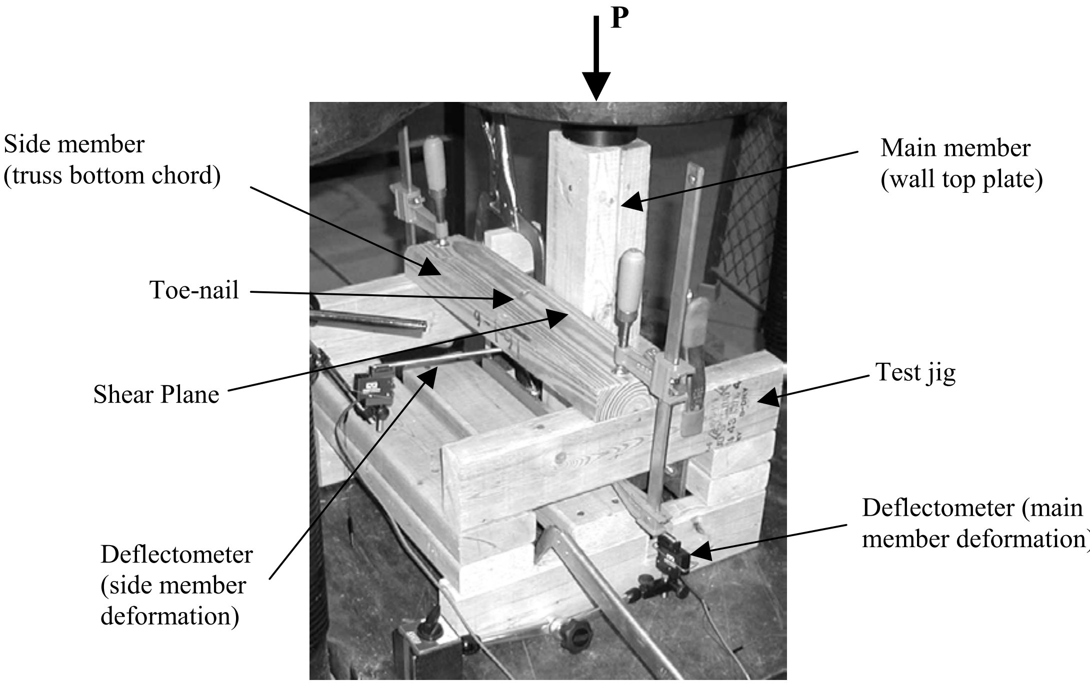

Figure 23
Setup for Individual Roof-to-Wall Connection Tests

Center portions of several bottom chords of the trusses used in the roof-to-wall connection system tests (Section 3.2) were cut into 18-inch-long sections and used to fabricate individual roof-to-wall connection specimens. These 18-inch-long 2-inch by 4-inch nominal size SYP sections were connected to 24-inch-long, double 2-inch by 4-inch nominal size top plates made with SPF lumber using two toe-nailed connections assembled with: (1) two 16d pneumatic nails or (2) three 8d common nails. Therefore, a specimen consisted of two members: side member, which represented the truss bottom chord, and main member, which represented the wall top plate.

A test jig was fabricated to accommodate the test specimens in the UTM. A vertical compression load was applied to the side member at a constant displacement rate of 0.2 in/min. To estimate the relative connection slip, two deflectometers were used to measure displacements of the side and main members, respectively. The difference in the deflection readings was the joint slip and was used to plot the load-deformation curves. Load and displacement measurements were collected by the UTM data acquisition system. Ten specimens were tested for each specimen configuration. For test configuration 2 with three 8d nails per connection, five of the specimens were tested with two nail heads facing up and five were tested with one nail head facing up and the results were averaged. The averaging was justified because there was little difference identified in the peak load between the two loading configurations. These component test specimens differed from system test conditions in that the toe-nails were not located near the beveled end of the truss chord member. But, this component test condition was consistent with the NDS provisions for use of the toe-nail factor, K_{tn}.

4.3.3 Results and Discussion

Two configurations of individual roof-to-wall connections were tested in correspondence with roof system test configurations 1 and 2 (Table 16) with two 16d pneumatic nails and three 8d common nails per joint, respectively. Figures 24 and 25 display the load-displacement curves for the individual toe-nailed connections. Table 19 summarizes results of the testing.

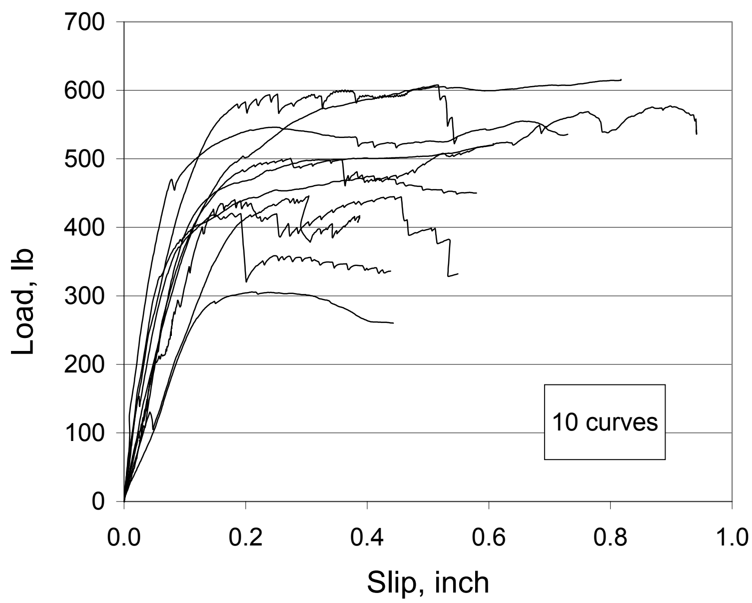

Figure 24
Load-Slip Relationships for Individual Roof-to-Wall Toe-Nail Connections Assembled with 2-16d Pneumatic Nails – Configuration 1

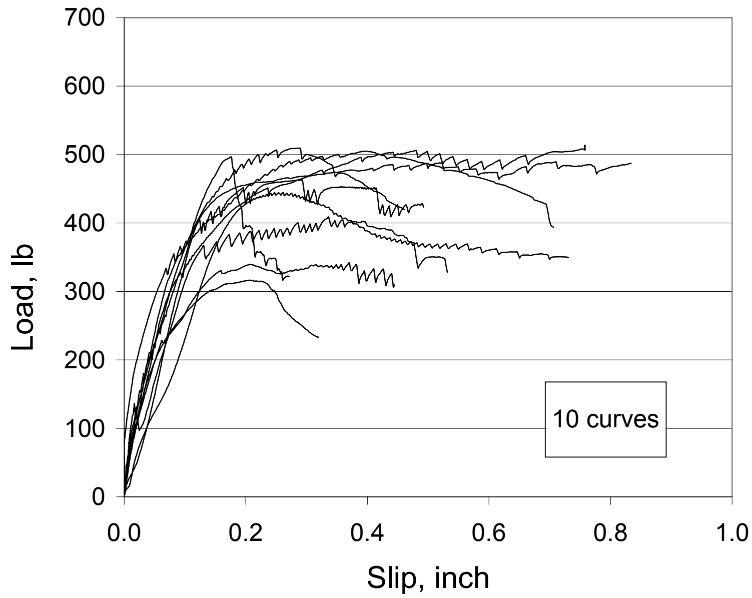

Figure 25
Load-Slip Relationships for Individual Roof-to-Wall Toe-Nail Connections Assembled with 3-8d Common Nails – Configuration 2

TABLE 19
RESULTS OF INDIVIDUAL ROOF-TO-WALL TOE-NAILED CONNECTION TESTS

CONFIG. #	CONNECTION	SAMPLE SIZE	AVERAGE PEAK LOAD, LB		AVERAGE DISPLACEMENT @ PEAK LOAD, INCH	
			Mean	COV, %	Mean	COV, %
1	2-16d pneumatic nails (toe-nailed)	10	499	19.4	0.498	49.5
2	3-8d common nails (toe-nailed)	10	449	15.9	0.380	52.4

The statistical analysis of variance (ANOVA) showed that the average peak loads of the connections assembled with 2-16d pneumatic (499 lb) and 3-8d common (449 lb) nails were not significantly different (P-value = 0.20 > 0.05). This finding confirmed the results of the full-scale roof system tests that also identified only a marginal difference in the average peak loads between these two nailing schedules (Table 16). The coefficient of variation for displacement at peak load of about 50 percent for both connections indicated high variability of stiffness characteristics for individual toe-nailed connections.

Table 20 includes the NDS allowable lateral design values for toe-nailed connections and the experimental average loads at 0.015-inch joint slip. Similarly to the results of heel joint tests (Section 4.2), the NDS allowable lateral design values overestimate the connection resistance at the 0.015-inch slip limit state. Furthermore, the disparity between the calculated and measured values is increased for toe-nailed connections as compared to face-nailed connections (Table 10) by as much as a factor of two. This effect can be explained with the change in failure modes from primarily lateral response of face-nailed connections to a combined lateral and withdrawal response of toe-nailed connections.

TABLE 20
NDS ALLOWABLE COMPARED TO 0.015 INCH SLIP TEST RESULTS

CONFIG. #	CONNECTION TYPE	CALCULATED NDS ALLOWABLE LATERAL DESIGN VALUE[1], LB	AVERAGE LOAD @ 0.015 IN. SLIP, LB (COV, %)	NDS/0.015 IN. SLIP (RATIO)
1	2-16d pneumatic nails (Toe-nailed)	230	80 (48.2)	2.88
2	3-8d common nails (Toe-nailed)	285	96 (41.3)	2.97

[1]See Appendix A for calculations.

Table 21 summarizes the safety margins for toe-nailed connections calculated as the ratio of the average peak load and the allowable design value. The average safety margin of 2.2 for the connections with 2-16d pneumatic nails is consistent with the intent of the building code, whereas the average safety margin of 1.6 for the connections with 3-8d common nails is below the accepted limit and indicates an inadequacy of the analysis methods for design of toe-nailed connections. Safety margins for both toe-nailed connections are lower that those determined for face-nailed connections. The unique attributes of the lateral response of toe-nailed connections that limit the applicability of the yield theory include the load direction effect, development of withdrawal load component under lateral loading, and reduced resistance to splitting of the side member when short edge distances are used (Figure 26). Because the average peak load of 16d pneumatic toe-nails was predicted more consistently relative to accepted safety margins, it can be suggested that the critical parameter that influences the resistance of a toe-nailed connection is the anchorage of the nail shank in the main member. Besides being coated with a polymer-based glue that provided an additional holding power, the 16d pneumatic nails had a penetration depth of approximately 0.5 inches greater than that of 8d common nails. Therefore, it is suggested to increase the current minimum required nail penetration for smooth-shank non-coated toe-nailed connections. As a preliminary recommendation, a minimum penetration depth of 16 nail diameters is proposed based on results of this testing program. The design values of toe-nails that do not meet this minimum penetration requirement should be adjusted with a reduction factor corresponding to the depth of penetration used. Based on this test data, a reduction factor of 1.3 should be used to adjust the lateral design resistance of 8d common toe-nails. This provision is intended as complementary to the current toe-nail adjustment factor of 0.83 [1]. Alternatively, an analysis for combined withdrawal and lateral loading can be performed.

TABLE 21
SAFETY MARGINS RELATIVE TO NDS ALLOWABLE

CONFIG. #	CONNECTION TYPE	CALCULATED NDS ALLOWABLE LATERAL DESIGN VALUE[1] (LB)	AVG PEAK LOAD (LB)	AVG PEAK LOAD/NDS RATIO (SAFETY MARGIN)
1	2-16d pneumatic nails (Toe-nailed)	230	499	2.19
2	3-8d common nails (Toe-nailed)	285	449	1.58

[1]See Appendix A for calculations.

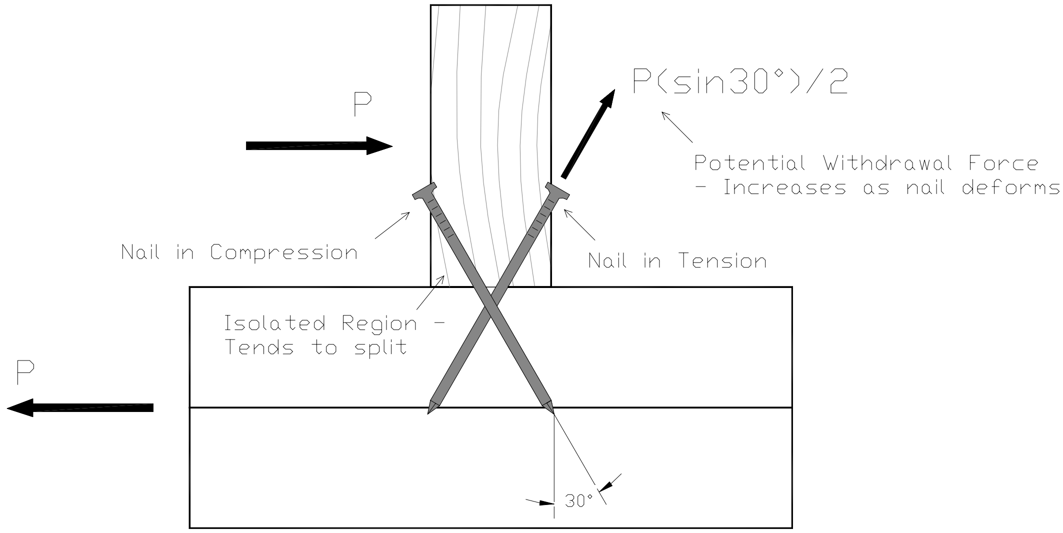

Figure 26
Toe-Nailed Joint Response

Table 22 compares the ultimate lateral resistance calculated using the yield theory and the average experimental peak loads. The ratio of predicted to measured values of 0.89 for 16d pneumatic nails indicates that the yield theory at the capacity limit state provides a conservative estimate of the average test peak load, which is also consistent with the results of the face-nailed heel joint tests (Section 4.2). In contrast, the yield theory overpredicted the ultimate resistance of toe-nailed connections assembled with shorter 8d common nails. This finding further supports the proposed increase for the minimum nail penetration requirement for toe-nailed connections. In effect, the purpose of the enhanced withdrawal resistance for toe-nailed connections is to ensure the response representative of the yield theory failure modes.

TABLE 22
COMPARISON OF CALCULATED AND MEASURED ULTIMATE LOADS

CONFIG. #	CONNECTION TYPE	YIELD EQUATION ULTIMATE VALUE[1], lb	AVG PEAK LOAD, lb	PREDICTED/ AVG PEAK LOAD RATIO
1	2-16d pneumatic nails (Toe-nailed)	447	499	0.89
2	3-8d common nails (Toe-nailed)	536	449	1.19

[1]See Appendix A for calculations.

To investigate potential system effects, the average peak loads for the individual roof-to-wall connections and full-scale roof systems are compared (Table 23). The unit resistance of the full-scale roof systems per toe-nailed joint was 78 and 63 percent lower than the average peak load measured for individual connections assembled with 2-16d pneumatic and 3-8d common nails, respectively. This effect may be attributed to differences in the assembly of individual toe-nailed connection specimens as opposed to the full-scale roof system tests. In particular, the toe-nails were located close to the beveled end of the truss bottom chord in the system tests and tended to prematurely split the wood member, whereas the individual specimens were assembled such that a sufficient edge distance was provided to minimize the splitting. The current NDS provisions [1] include a vague clause for placement of nails that requires “sufficient” end distances, edge distances, and spacing to "prevent splitting of the wood". The location of the truss plates directly above the wall and the beveled configuration of the truss heel joint limits the framing options for providing sufficient end distances. Therefore, the use of conventional roof-to-wall toe-nailed connections for fastening of engineered MPC trusses should be further investigated to develop connections that provide resistance consistent with the intent of the prescriptive construction provisions.

TABLE 23
COMPARISON OF SYSTEM ROOF-TO-WALL
AND INDIVIDUAL ROOF-TO-WALL CONNECTION

CONNECTION TYPE	INDIVIDUAL ROOF TO WALL CONNECTION AVG PEAK LOAD[1], lb	ROOF SYSTEM AVERAGE UNIT PEAK LOAD, lb/JOINT	RATIO OF PREDICTED/ TESTED
2-16d pneumatic	499	283	1.78
3-8d common	449	276	1.63

4.3.4 Conclusions

1. Analysis of variance (ANOVA) showed that the peak load of toe-nailed connections assembled with 2-16d pneumatic nails and 3-8d common nails are not significantly different (Table 19).

2. The NDS allowable design load showed a poor correlation with the experimental 0.015-inch slip limit values (Table 20).

3. The average safety margins for toe-nailed connections decreased compared to those for face-nailed connections and were estimated as 2.2 and 1.6 for 2-16d pneumatic and 3-8d common nails, respectively (Table 21). The reduced resistance of the toe-nailed connections relative to the yield theory is explained with the unique attributes of the toe-nail connection response including load direction effect, development of withdrawal load component under lateral loading, and reduced edge distances (Figure 26).

4. It is recommended to increased the minimum nail penetration requirement into the main member to 16 nail diameters for toe-nailed connections to develop full lateral resistance representative of the yield theory approach. The design values of toe-nails that do not meet this minimum penetration requirement should be adjusted with a reduction factor corresponding to the depth of penetration used. Based on this test data, a reduction factor of 1.3 should be applied to adjust the lateral design resistance of 8d common toe-nails. This provision is intended to be in addition to the current toe-nail adjustment factor of 0.83 [1].

5. Based on comparison of the full-scale system test and individual roof-to-wall connection test results, the resistance of a toe-nailed connection in a system of MPC trusses is as much as 80 percent lower than that of an individual toe-nailed connection. This reduction is attributed to the decreased end distances in the truss heel joint that precipitate premature wood splitting at the beveled end of the bottom truss chord.