5.0 SUMMARY AND CONCLUSIONS

The analytical and experimental findings of this project provide an opportunity to advance the engineering knowledge in the field of wood connections used by the residential building industry. As conventional residential construction evolves to incorporate recent technological advances and as houses become engineered to include enhanced connection requirements and novel fastening systems, the updated engineering information becomes important. This information should be used to provide consistent basis for connection design with respect to historical practice and innovative design methodologies.

Under this project, several research areas are identified and investigated to benchmark the response of conventional and engineered roof connections. Three research tasks are completed on the performance of heel joints, full-scale roof-to-wall connections, and individual toe-nailed roof-to-wall connections. Results of the investigation indicate several inconsistencies in the design methodologies used for engineering analysis of traditional and hardware-type connections that can potentially lead to development of inaccurate prescriptive connection provisions and inefficient design solutions. As a method to reconcile many of the detected disparities, it was proposed to implement capacity-based design methodology for analysis of all types of wood connections. This recommendation is supported with results of the literature survey and experimental program. As capacity-based design provides a measure of safety with improved consistency, the greatest practical impact will be realized in high-seismic and hurricane-prone areas where economical engineering solutions are essential for construction of safe and affordable housing.

Task 1 demonstrated that conventional practice of constructing roof heel joints with 3-10d common nails (or equivalent) should be limited by building geometry and geographical regions. System effects such as attachment of the heel joint members to the wall assembly should be included in the analysis to accurately predict the resistance of conventional connections on a capacity basis.

Results of Task 2 show that the resistance of roof-to-wall toe-nailed connections (direction parallel to wall) used with MPC wood trusses can be decreased as compared to conventional rafter-joist roof systems due to reduced edge distances and limited area for nail installation. Therefore, a prescriptive connection schedule should be developed for attachment of MPC trusses to provide lateral resistance equivalent to the conventional roof systems. It is further shown that a simple hurricane clip can be used in the high-hazard regions to significantly improve the lateral load transfer from the roof diaphragm to shear walls in conventional residential construction.

Task 3 manifests that the current engineering methods for design of toe-nailed connections should be revised to account for unique response attributes such as increased withdrawal force, reduced edge distance, directionality effects, etc. The current design methods can potentially overestimate the resistance of certain toe-nailed connections and result in safety margins lower than intended by building codes.

6.0 RECOMMENDATIONS

The findings of this report can be applied to re-evaluate or confirm connection requirements for conventional construction, such as roof connections investigated under this project, with a practical view toward historic practice, structural performance, and constructability. The re-evaluation should include improvements to the ability to design wood connections to an explicit and consistent safety margin relative to failure. For example, the NDS method for design of wood connections in shear using the yield equations, particularly for the types of joints considered in this study, should be modified as follows:

1. Use ultimate dowel bearing and ultimate nail bending values to predict connection shear capacity.

2. Apply a consistent safety margin, such as 2.0 as recommended in this study, to adjust connection capacity estimates to an allowable design value for residential construction.

3. Use all applicable adjustment factors as specified in the NDS provisions [1].

4. In coordination with the above changes to the NDS procedure, include a method to estimate and limit joint slip as an independent design check dependent on application requirements and performance objectives consistent with residential construction practice and other related experience.

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APPENDIX A
CALCULATION OF LATERAL NAIL CONNECTION VALUES

This appendix summarizes the calculations of lateral resistance of nail connections used in the testing program. The lateral resistance is determined for three limit states: NDS design limit state, 5 percent nail diameter offset limit state, and ultimate limit state (i.e., capacity). According to the yield theory, yield mode IV (refer to [1] for definition of yield modes) governs the response of connections investigated under this project. The resistance of a single dowel connection in yield mode IV can be calculated as follows:

$$P = D^2 \sqrt{\frac{2\, F_{em}\, F_b}{3\,(1+R_e)}} \qquad \text{(A1)}$$

where:

R_e	$= F_{em}/F_{es}$;
F_{em}	= dowel bearing strength of main member;
F_{es}	= dowel bearing strength of main member;
D	= nail diameter;
F_b	= nail bending strength.

Resistance of other yield modes (III_m and III_s) is also calculated for several connection configurations for reference purposes. Equations used in the calculations can be found in the NDS [1]. To determine the resistance at a limit state under consideration, Equation A1 is used with the material properties at the corresponding limit state and applicable adjustment factors. The NDS allowable design value for a multiple nailed connection is calculated as follows:

$$Z' = \frac{n\,P}{K_D}\, C_D\, C_M\, C_t\, C_d\, C_{eg}\, C_{di}\, C_{tn} \qquad \text{(A2)}$$

where:

n	= number of nails in a connection or system of connections under consideration;
P	= load resistance determined using Equation (A1) with $F_e = F_{e,5\%}$ and $F_b = F_{b,5\%}$ (refer to Sections 3.4 and 4.1);
$F_{e,5\%}$	= 5 percent offset dowel bearing strength;
$F_{b,5\%}$	= 5 percent offset dowel bending strength;
$K_D = 2.2$	= calibration factor – for nails under 0.16 inch in diameter;
$C_D = 1.6$	= load duration factor – adjusts for short-term duration of tests;
$C_M = 1.0$	= wet service factor – moisture content of lumber was < 19 %;
$C_t = 1.0$	= temperature factor – temperature during testing was < 100^oF ;
$C_d = p/(12D)$	= penetration depth factor – penetration varied between the tests;
p	= nail penetration into the main member;
D	= nail diameter;
$C_{eg} = 1.0$	= end-grain factor – connections did not include nails installed into end grain;
$C_{di} = 1.0$	= diaphragm factor – not applicable to tested connections;
$C_{tn} = 0.83$	= toe-nailed factor – used with all toe-nailed connections.

The resistance of a multiple nailed connection at 5 percent nail diameter offset limit state is calculated as follows:

$$P_{5\%}' = n\, P\, C_M\, C_t\, C_d\, C_{eg}\, C_{di}\, C_{tn} \tag{A3}$$

where:

n, P, C_{M}, C_t, C_d, C_{eg}, C_{di}, C_{tn} = refer to Equation A2.

The resistance of a multiple nailed connection at ultimate load limit state is calculated as follows:

$$P_{ult} = n\, P\, C_M\, C_t\, C_d\, C_{eg}\, C_{di}\, C_{tn} \tag{A4}$$

where:

n, C_{M}, C_t, C_d, C_{eg}, C_{di}, C_{tn}	= refer to Equation A2.
P	= load resistance determined using Equation (A1) with $F_e = F_{e,ult}$ and $F_b = F_{b,ult}$ (refer to Sections 3.4 and 4.1);
$F_{e,ult}$	= ultimate dowel bearing strength;
$F_{b,ult}$	= ultimate dowel bending strength.

The calculations are organized in three groups to correspond to the tasks under the testing program: heel joint connections, full-scale roof-to-wall connections, and individual roof-to-wall connections. Results are presented in a table format. The adjustment factors, which are not directly applicable to the tested connection configurations and equal to unity, are not included.

1. RAFTER-TO-CEILING JOIST CONNECTION (HEEL JOINT) TESTS

TABLE A1
NDS ALLOWABLE VALUES FOR INDIVIDUAL NAILS

Nail	D, in	$F_{em,5\%}$, psi	$F_{es,5\%}$, psi	$F_{b,5\%}$, psi	K_D	C_D	C_d	C_{tn}	Z', lb		
									III_m	III_s	IV
8d common – toe-nailed	0.131	3,665	3,665	81,491	2.2	1.6	0.85	0.83	120	**85**	87
10d common	0.149	3,665	3,665	80,639	2.2	1.6	1.0	1.0	220	220	**160**
16d pneumatic	0.132	3,665	3,665	83,691	2.2	1.6	1.0	1.0	191	191	**128**
16d pneumatic – toe-nailed	0.132	3,665	3,665	83,691	2.2	1.6	1.0	0.83	180	123	**106**

TABLE A2
5 PERCENT OFFSET VALUES FOR INDIVIDUAL NAILS

Nail	D, in	$F_{em,5\%}$, psi	$F_{es,5\%}$, psi	$F_{b,5\%}$, psi	C_d	C_{tn}	Z', lb		
							III_m	III_s	IV
8d common – toe-nailed	0.131	3,665	3,665	81,491	0.85	0.83	165	**118**	120
10d common	0.149	3,665	3,665	80,639	1.0	1.0	302	302	**220**
16d pneumatic	0.132	3,665	3,665	83,691	1.0	1.0	263	263	**176**
16d pneumatic – toe-nailed	0.132	3,665	3,665	83,691	1.0	0.83	247	169	**146**

TABLE A3
ULTIMATE VALUES FOR INDIVIDUAL NAILS

Nail	D, in	$F_{em,ult}$, psi	$F_{es,ult}$, psi	$F_{b,ult}$ psi	C_d	C_{tn}	Z', lb		
							III_m	III_s	IV
8d common – toe-nailed	0.131	5,510	5,510	108,772	0.85	0.83	246	173	**170**
10d common	0.149	5,390	5,390	108,357	1.0	1.0	440	440	**310**
16d pneumatic	0.132	5,503	5,503	118,300	1.0	1.0	393	393	**257**
16d pneumatic – toe-nailed	0.132	5,503	5,503	118,300	1.0	0.83	369	251	**213**

TABLE A4
RESISTANCE OF TWO PARALLEL HEEL JOINTS

Config. #	Rafter-to-Joist Connection (Heel Joint)	Number of joints	NDS Allowable Value, lb			5% Offset Value, lb			Ultimate Value, lb		
			III_m	III_s	IV	III_m	III_s	IV	III_m	III_s	IV
1	3-10d Common Nails Unattached	2	1,317	1,317	**962**	1,812	1,812	**1,322**	2,643	2,643	**1,859**
2	3-10d Common Nails Attached with 3-8d Common Toe-Nails	2	1,489	1,489	**1,133**	2,047	2,047	**1,558**	2,984	2,984	**2,200**
3	3-16d Pneumatic Nails Unattached	2	1,147	1,147	**769**	1,577	1,577	**1,057**	2,357	2,357	**1,540**
4	3-16d Pneumatic Nails Attached with 3-16d Pneumatic Toe-Nails	2	1,360	1,360	**981**	1,869	1,869	**1,350**	2,783	2,783	**1,966**
5	12-16d Pneumatic Nails Unattached	2	4,587	4,587	**3,075**	6,308	6,308	**4,228**	9,428	9,428	**6,160**

2. FULL-SCALE ROOF-TO-WALL CONNECTION SYSTEM TESTS

TABLE A5
NDS ALLOWABLE VALUES FOR INDIVIDUAL NAILS

Nail	D, in	$F_{em,5\%}$, psi	$F_{es,5\%}$, psi	$F_{b,5\%}$, psi	K_D	C_D	C_d	C_{tn}	Z', lb		
									III_m	III_s	IV
8d common – toe-nailed	0.132	3,075	6,093	81,491	2.2	1.6	0.85	0.83	113	113	**92**
12d pneumatic toe-nail	0.131	3,075	6,093	90,596	2.2	1.6	1.0	0.83	151	151	**97**
16d pneumatic – toe-nailed	0.120	3,075	6,093	83,691	2.2	1.6	1.0	0.83	168	167	**112**

TABLE A6
ULTIMATE VALUES FOR INDIVIDUAL NAILS

Nail	D, in	$F_{em,5\%}$, psi	$F_{es,5\%}$, psi	$F_{b,5\%}$, psi	K_D	C_D	C_d	C_{tn}	$P'_{5\%}$, lb		
									III_m	III_s	IV
8d common – toe-nailed	0.132	4,976	7,405	108,772	2.2	1.6	0.85	0.83	239	205	**177**
16d pneumatic – toe-nailed	0.120	4,969	7,395	118,300	2.2	1.6	1.0	0.83	357	302	**221**

TABLE A7
RESISTANCE OF FULL-SCALE ROOF-TO-WALL SYSTEM CONNECTIONS

Config. #	Roof-to-Wall Connection	NDS Allowable Value, lb	Ultimate Value, lb
1	22-16d pneumatic nails Toe-nailed (2 per truss)	**2,470**	**4,871**
2	33-8d common nails Toe-nailed (3 per truss)	**3,051**	**5,850**
3	22-12d pneumatic nails, toe-nailed (2 per truss) 9-H2.5 Hurricane Clips (at interior trusses)	**1,170 – HC[1]** **2,124 – TN[2]** **(3,294 – HC+TN)[3]**	**n/a[4]**
4	4-12d pneumatic nails, toe-nailed (2 per end truss) 9-H2.5 Hurricane Clips (at interior trusses)	**1,170 – HC[1]** **386 – TN[2]** **(1,556 – HC+TN)[3]**	**n/a[4]**

[1]Based on resistance of hurricane clips. Hurricane clip resistance is adopted from manufacturer's specifications [34].
[2]Based on resistance of toe-nails.
[3]Based on superposition of toe-nails and hurricane clips. The values are given is parenthesis because the NDS does not permit superposing mixed fasteners [1].
[4]Capacity of hurricane clips is not reported by the manufacturer.

3. INDIVIDUAL ROOF-TO-WALL TOE-NAILED CONNECTION TESTS

TABLE A8
NDS ALLOWABLE VALUES FOR INDIVIDUAL NAILS

Nail	D, in	$F_{em,5\%}$, psi	$F_{es,5\%}$, psi	$F_{b,5\%}$, psi	K_D	C_D	C_d	C_{tn}	Z', lb		
									III_m	III_s	IV
8d common – toe-nailed	0.132	4,301	4,301	81,491	2.2	1.6	0.85	0.83	139	98	**95**
16d pneumatic – toe-nailed	0.120	4,301	4,301	83,691	2.2	1.6	1.0	0.83	209	141	**115**

TABLE A9
ULTIMATE VALUES FOR INDIVIDUAL NAILS

Nail	D, in	$F_{em,5\%}$, psi	$F_{es,5\%}$, psi	$F_{b,5\%}$, psi	K_D	C_D	C_d	C_{tn}	$P'_{5\%}$, lb		
									III_m	III_s	IV
8d common – toe-nailed	0.132	6,047	6,047	108,772	2.2	1.6	0.85	0.83	268	187	**179**
16d pneumatic – toe-nailed	0.120	6,040	6,040	118,300	2.2	1.6	1.0	0.83	403	273	**223**

TABLE A10
RESISTANCE OF INDIVIDUAL ROOF-TO-WALL SYSTEM CONNECTIONS

Config. #	Roof-to-Wall Connection	NDS Allowable Value, lb	Ultimate Value, lb
1	2-16d pneumatic nails (toe-nailed)	230	447
2	3-8d common nails (toe-nailed)	285	536