Chapter 5 – Summary and Conclusions

5.1 – Summary

The objectives of this research were: 1) to develop physical data on the behavior and mechanics of nailed and bolted single-shear laterally-loaded connections up to and beyond capacity, and 2) to quantify safety factors and over-strengths of design values currently stipulated by the NDS® and LRFD manual for wood construction. A total of six-hundred-eighty-one single-shear, single-fastener connections were tested monotonically in tension to accomplish the first objective. These connection specimens represented a wide array of configurations commonly used in wood construction. Test variables included variations of fastener type and diameter, and main and side member material type and dimensions, accordingly. Tests were also conducted to determine the material properties and moisture contents of connection components. Namely, these tests were: 1) embedment tests for determining the embedment strength, or bearing strength, of each connection specimen's main and side members, 2) fastener bending tests for determining the average plastic bending moment of fastener type used, and 3) specific gravity and moisture content tests. Values derived from embedment and fastener bending tests were used to calculate theoretical resistances at 5% offset yield for each connection according to the yield theory. Based upon the assumption that the same yield modes which act to provide resistance at 5% offset yield also account for the resistance observed at capacity, theoretical values were calculated for connection resistance at capacity as well. Design values were then calculated based upon theoretical 5% offset yield resistances and compared to observed connection capacities in order to accomplish the second objective.

5.2 – Conclusions

5.2.1 – Connection Test Results

Various parameters for characterization of connection behavior up to and beyond capacity were attained. Summaries of these parameters, including averages and COVs of elastic stiffness, ductility ratios, and resistance at 5% offset yield, capacity, and failure were presented in Chapter 4. Trends in said parameters with respect to test variables were discussed. Average load-deflection plots for each connection configuration were also presented and discussed. Among the major trends observed were the following;

- Gypsum wallboard and fiberboard connections often exhibit a mode shift from Mode I_s to Mode III_s between 5% offset yield and capacity. This is a result of compaction, or densification, of material at the bearing interface within the side member. It has a profound influence on connection response, as the formation of a plastic hinge within the dowel limits capacity resistance, but increases ductility ratios.
- The presence of embedded fibers within gypsum wallboard appears to increase connection resistance, especially at capacity, and also increases the likelihood of yield mode shift.
- A significant increase in resistance, and decrease in ductility was observed with respect to nail diameter (between ϕ = 0.099" and 0.131") in hardboard connections. This is due to the fact that, while *all* hardboard connections exhibited Mode III_s yield, larger diameter nails, because of their greater plastic bending moments, tend to crush the material at the bearing interface, thereby resulting in a marked decrease in bearing resistance after capacity is reached.
- OSB and plywood connections yielding by Mode IV (i.e., those with thick side members) reached capacity at much greater deflections than those yielding by Mode III_s. Although unquantifiable due to limitations in the displacement range of testing equipment, the *ductility* of these connections is most likely greater as well.
- The capacities of nailed connections are typically between 1.9 and 2.0 times their 5% offset yield resistance values. This is demonstrated in Section 4.2.6 where the linear regression fitted to data of capacity resistance versus 5% offset yield resistance for all nailed connections has a slope of 1.93.
- For bolted connections, capacities are typically between 1.6 and 1.8 times their 5% offset yield values. This is demonstrated in Section 4.3.1 where the linear regression fitted to data of capacity versus 5% offset yield is 1.71.

Although the theory was not tested in this research, observed resistances of bolted connections at high deflections are apparently increased by: 1) the increase in friction between the two members brought about by the horizontal component (perpendicular to loading direction) of axial tension within the rotated bolt, and 2) resistance provided directly through the increasing vertical component (parallel to loading direction) of axial tension within the bolt. Resistance increases due to these factors is greatest in connections having thin main members and large bolt diameters (i.e., connection sets 05-11 and 05-22).

5.2.2 – Evaluation of the Yield Theory at Capacity

The following conclusions are made regarding the applicability of the yield theory for predicting capacity resistance of single shear nailed and bolted connections:

- When applied on a capacity-basis, the yield theory *usually* under-predicts capacity resistance; with calculated-to-tested (C/T) ratios ranging from 0.55 to 1.0 in nailed connections, and from 0.37 to 0.75 in bolted connections. This under-prediction is expected, as the yield model assumes small deflections, and thus does not account for friction or the vertical component of axial tension within the fastener.
- Of nailed connections, the lowest C/T ratios (evaluated at capacity) are observed in those having hardboard side members. These low C/T ratios, however, are most likely a result of the greater extent to which crushing occurred within hardboard embedment specimens, resulting in decreased apparent embedment strengths. Had the true bearing strengths of these specimens been quantifiable (i.e., as determined by full-hole tests), hardboard C/T ratios would most likely have been closer to 1.0, as were those of OSB and plywood connections.
- As noted in Section 4.7.2, C/T ratios of nailed connections with plywood side members were greater than those with OSB side members when evaluated at 5% offset yield. The same trend was not apparent in C/T ratios evaluated at capacity, where plywood and OSB connections had approximately the same C/T ratios.
- C/T ratios evaluated at capacity decrease with respect to fastener diameter in nailed connections exhibiting Mode III_s yield. Conversely, no significant difference in

C/T ratios with respect to nail diameter was observed in connections exhibiting Modes I_s or IV.

- C/T ratios of bolted connections significantly decrease with respect to bolt diameter in connections having thin members. This trend is of decreasing significance for connections with greater member thickness. This is explained by the greater increase in test resistances at higher deflections in connections with thin members and large diameter bolts, as described in Section 4.7.2.2 and mentioned in Section 5.2.1.
- With an R-squared value of 0.929, the linear correlation between theoretical capacity resistance and theoretical 5% offset yield resistance for all nailed connections corresponds to a ratio of 1.32. For bolted connections, this same ratio is 1.03, where the least-squares regression has an R-squared value of 0.987. For both nailed and bolted connection data, R-squared values indicate strong linear correlations.

5.2.3 – Quantification of Over-Strengths

A comparison of design values (based upon yield model calculations at 5% offset yield) to capacity resistance reveals the following:

- Trends in observed factors of safety and over-strengths are, in most cases, inversely proportional to trends observed in C/T ratios. Minor deviations do exist due to the fact that these values represent a cross-wise comparison between theoretical 5% offset yield resistance and actual capacity resistance.
- Over-strengths of nailed connections in gypsum wallboard, fiberboard, and hardboard ranged from 1.2 to 1.8; whereas all other tested nailed configurations have over-strengths of between 0.86 and 1.2. Relatively high over-strengths in gypsum wallboard, fiberboard, and hardboard connections are the result of greater resistance increases (greater than those accounted for by the factor of 3.3 discussed in Section 2.3.3) between 5% offset yield and capacity due to bearing compaction.
- Of those configurations tested, bolted connections have over-strengths ranging from 1.3 to 3.0. Over-strengths significantly increase with respect to main member

thickness in connections having large diameter ($\phi = {}^{5}/_{8}$”) bolts. The same trend is not as pronounced in connections having small diameter ($\phi = {}^{3}/_{8}$”) bolts.

- While differences in average over-strengths with respect to yield mode are significant in all cases (for both nailed and bolted connections), the difference is much greater in bolted connections. The observed average over-strength of bolted connections yielding by Mode II is 2.0, while that of bolted connections yielding by Mode III is 1.4. T-tests confirmed this difference with a p-value smaller than 10^{-3}.

5.3 – Limitations

Limitations of this research are as follows:

- All connections were tested monotonically.
- Only single-shear configurations were investigated.
- Fasteners used in connection specimens were nails and bolts (i.e., connections with spikes, lag screws, wood screws, etc. were not investigated) from limited manufacturers and few batches.
- Only materials and commercial species groups that are common in construction (i.e., SPF, Southern Pine, and Mixed Southern Pine) were used.
- Although all specimens were conditioned in the same chamber prior to testing, moisture contents were somewhat variable within connection members due to differences in their equilibrium moisture contents (EMC).

5.4 – Recommendations for Future Work

In light of the observation that over-strengths of bolted connections vary significantly with respect to yield mode, investigations should be made on over-strengths corresponding to Modes I and IV in bolted connections.

The comparison of actual capacity resistance to theoretical capacity resistance presented the current work has revealed trends in ratios between the two values with respect to connection geometry and material properties. These trends are explainable on a mechanics basis, and may thus lend themselves to being modeled in this way. Upon development of additional data on Modes I and IV for bolted connections, such a model may be integrated with, or superimposed onto, the yield model. Thus, further research should also be conducted to isolate and quantify the effects of friction between the two members and resistance provided directly through the increasing vertical component (parallel to loading direction) of axial tension within the bolt at high deflections (i.e., near capacity).

Additional research should also continue to focus on the capacity resistance of connections subjected to cyclic loading, as results from such tests shed light on the behavior of connections during seismic events.

Finally, future studies should build upon this research with the ultimate goal of adaptation of reliability-based design concepts to laterally-loaded connection design. Average over-strengths for various connection configurations, as well as the inherent variabilities associated with each, must be accounted for in order to accomplish this.