

Chapter 5 Summary, Conclusions, and Recommendations

5.1 – Summary

The primary objective of this research was to experimentally quantify the significance of the group action factor at capacity, in multiple bolt timber connections exposed to cyclic loading. Two hundred and thirteen full-scale joint specimens with variable side members, main member thickness, numbers of bolts, and number of rows, were tested using monotonic (unidirectional) and CUREE cyclic protocol procedures. In addition, material property tests were conducted to determine the moisture content, specific gravity, and dowel embedment strength of wood specimens as well as bolt bending tests. Load-deflection data was obtained from a load cell on the testing machine and two potentiometers positioned to acquire a relative displacement between moving timber members. Data analysis included determination of performance indicators including capacity, equivalent energy elastic-plastic yield strength, 5% offset yield strength, ductility, cyclic stiffness, and energy dissipation characteristics.

5.2 – Conclusions

5.2.1 – Group Action Factor at Capacity

The number of bolts influences connection capacity as follows:

- Single-bolt connection capacity cannot be directly extrapolated to predict multiple-bolt connection capacity.
- The greatest decrease in maximum load per fastener was determined to be when the number of bolts was increased from one to three.
- When the number of bolts was increased from three to five the decrease in maximum load per fastener was typically not significant.

- A step function group action factor with a single step of 0.60 could be developed for multiple-bolt connections.
- There is no significant reduction in capacity associated with row interaction (4D row spacing).

5.2.2 – Group Action Factor at 5% Offset Yield Strength

The number of bolts influences connection 5% offset yield strength as follows:

- The comparison of 5% offset yield strength between single-bolt and multiple-bolt connections is inconsistent because the parameter itself is dependent upon other variable parameters and limited by connection capacity. However, the group action factor for 5% offset yield could be eliminated with minor adjustments to the design value.
- Comparisons between single-row and multiple-row connections were inconsistent due to the limitations described above.

5.2.3 – Ductility Ratio Trends

The number of bolts influences ductility ratio as follows:

- The ductility ratio of a single-bolt connection is significantly larger than that of a multiple-bolt connection.
- There is no significant reduction in ductility ratio associated with row interaction (4D row spacing).
- The similarities between ductility ratio trends and the group action factor based on connection capacity indicate that a further review of spacing between bolts in a row is warranted. Current NDS (1997) recommendations for spacing of bolts in a row, utilized throughout this study, specify a 4D, or four times the bolt diameter, center-to-center bolt spacing. A review of single-bolt and multiple-bolt connection performance in this study indicates that an increase in bolt spacing from 4D to 7D would enhance multiple-bolt connection performance by allowing more redistribution of bolt forces by limiting the likelihood of premature brittle failure. A parallel study by Heine (2001) that modeled multiple-bolt connections

also indicated that a minimum spacing of 4D was inadequate and should be increased to 7D for optimum performance.

5.2.4 – Yield Limit Model Predictions

Inferences concerning the Yield Limit Model are as follows:

- The Yield Limit Model underestimates the capacity of single-shear, single-bolt wood connections exposed to cyclic loading.
- Testing indicates that the Yield Limit Model may be able to predict the 5% offset yield strength of single-shear single-bolt connections exposed to cyclic loading. Deviations between test and prediction may be attributed to sampling and material testing procedures.

5.2.6 – Yield Mechanisms

This study has shown that expected yield modes and actual yield modes are two different things. To supplement the primary objective of this research an attempt was made to design connections that yielded in three of the four mechanisms outlined in the NDS (1997), namely yield modes II, III, and IV. As noted, testing of joints expected to yield according to mode II were relatively straightforward to identify and observe. Testing of joints expected to correspond to yield modes III and IV require further discussion.

Post-test examination of single-shear, multiple-bolt timber connections exposed to cyclic loading in which one or more plastic hinges were expected to develop as part of the yielding mechanism, typically showed a mixed yield mode phenomenon. It appeared that the bolts would yield by migrating through the yield modes from mode II to mode IV. In connection with a mixed mode yield form, the specimen typically failed due to splitting before all of the bolts could yield in the highest mode. Had the spacing between bolts been larger, the connections with mixed mode yield may have reached a complete mode IV yield condition.

Single-bolt connection tests associated with an expected mode III yield were noted as undergoing mode IV yield. It is likely that end fixity provided by the washers and consequently by the steel side plate altered the assumed distribution of moment

through an individual bolt and created two plastic hinges. Multiple-bolt connections, also expected to perform according to mode III yield fall under the discussion above concerning mixed mode yield.

5.2.7 – Failure Mechanisms

This study has shown that brittle failure mechanisms are typical in single-shear, multiple-bolt timber connections exposed to cyclic loading. Observed failure mechanisms included member splitting, tension rupture, and block shear. It was typical of connections with these failure mechanisms to fail in a violent manner with no warning. Such failures, associated with low ductility ratios, are dangerous in earthquake prone regions and should be avoided whenever possible.

5.2.8 – Initial Stiffness

This study has shown that the 1997 NDS recommendations for load-slip modulus, used in conjunction with the Lantos model, produce overly conservative group action factor values when used to predict the proportional limit behavior of single-shear, multiple bolt timber connections. The slip modulus used to determine the GAF that is currently recommended by the 1997 NDS is 4 to 6 times higher than the stiffness measured in single-bolt tests.

5.3 – Limitations of Research

Limitations of the research conducted herein, include:

- Only single-shear connections were tested.
- Study did not include 2 and 4 bolts per row connection configurations.
- Wood material was limited to one species (i.e., Southern Yellow Pine).
- Moisture content only ranged from 12% ~ 15%.

5.4 – Recommendations for Future Research

Future research on bolted timber connections should focus on optimizing the spacing of bolts in a row so that connection performance is improved at capacity. An

increase in the spacing of bolts in a row may decrease the effect of the group action factor at capacity by minimizing the likelihood of premature brittle failure. Spacing between rows of bolts was not a limiting factor in this research although it is possible that smaller row spacing will affect both capacity and the group action factor at capacity.

In light of the important findings on the ability of the Yield Limit Model to predict connection capacity, derivation of the model should be expanded to include the effects of bolt end restraints and friction between members. This step in the evolution of the YLM is important for the future of a capacity based design procedure and for future application of the group action factor at capacity especially since the GAF is virtually useless without an accurate model of single-bolt connection performance.

Additional research is needed to further understand failure mechanisms such as block shear and tension rupture. Similar to a limit state design, associated with steel connections, procedures should be established to ensure that the resistance provided by a connection for each limit state assumption is larger than the expected load.

Finally, it is important to expand the research conducted herein to multiple-shear connections so that a broader scope of bolted wood connections is both researched and understood. Continued understanding of both single-shear and multiple-shear bolted wood connections at capacity will enhance their safety and reliability, especially in earthquake prone regions.