Chapter 5 – Summary, Conclusions, and Recommendations

5.1 Summary

The primary focus of this research was to investigate whether a more optimum spacing for multiple-bolt timber connections subjected to reverse cyclic loading could be determined than the current design standard of spacing bolts at 4 times the bolt diameter. Three different connection configurations were tested under reverse cyclic loading with spacing ranging from 3D to 8D for a total of 150 tests. The loading protocol was in accordance with CUREE cyclic testing procedures. Forty-five monotonic tests were also performed to supply data for the cyclic tests. In addition to the connection tests, testing was also completed for material properties to determine moisture content, specific gravity, dowel embedment strength, and bolt bending strength. Results were analyzed to determine several parameters; maximum load, failure load, E.E.P. yield load, 5% offset load, elastic stiffness, E.E.P. energy, and ductility ratio. Statistical analysis was performed on results to investigate whether a more optimum spacing could be suggested.

5.2 Conclusions

Four objectives were stated at the beginning of this research. The conclusions and determinations are discussed herein.

First, spacing was determined to affect four of the seven strength and serviceability parameters: maximum load, 5% offset load, E.E.P. yield, and E.E.P. energy. Three parameters; failure load, elastic stiffness, and ductility ratio, were found to not be affected by differences in spacing between bolts in multiple-bolt, single-shear connections subjected to reverse cyclic loading. Failure in nearly all the connections tested occurred by splitting of the wood along the centerline of the bolts thus suggesting that failure is a function of wood characteristics and not influenced by the layout of the connection. Therefore, the failure load was not affected by the spacing. Because ductility ratio is a function of displacement at failure, the parameter is also not influenced by spacing of bolts. The elastic stiffness parameter was also found to be uninfluenced by spacing suggesting that the parameter is also a function of wood characteristics. The elastic stiffness parameter is a measurement of the slope of the initial linear portion of the load-displacement curve and is influenced by the bolts bearing on the wood fibers. The spacing between the bolts did not affect the interaction between the bolts and the wood fibers.

The second objective was to determine whether a statistical difference exists between results for the 4D spacing as generated by Anderson's (2002) research as compared to results for the spacings examined in this research. For the expected Yield Mode II and Yield Mode III tests, the results for the four parameters that were determined to be affected by spacing showed that the larger spacings; 5D, 6D, 7D, and 8D, performed more optimally than the 4D spacing. For the expected Yield Mode IV tests, the results were inconclusive. It should be noted that the connection layouts in the tests performed by Anderson (2002) and this research were not identical. Also, Yield Modes III and IV were not obtained in either research.

The third objective was to determine which of the five spacings; 8D, 7D, 6D, 5D, and 3D, produced the most optimal results. A discussion on how optimization was determined can be found at the beginning of chapter four. Generally, the 7D spacing was found to be most optimal. Tests for the 7D spacing resulted in higher values of E.E.P. energy than the other tested spacings, thus, the connections maintained longer periods of yielding before failure finally occurred. Therefore, the 7D spacing between bolts is most optimal when the maximization of energy is of concern as in seismic or wind design. Higher yield load values were also observed with the 7D spacing, thus, in order to maximize the duration of the linear-elastic period of loading, the results suggest that the 7D spacing is most optimum. For the maximum load parameter, the 7D and 6D spacing performed similarly. Results for the 5% offset load showed that the 6D spacing performed most optimal. See Table 5.1 for results.

Some tests resulted in large variations between data points for the 7D spacing, thus, the Tukey analysis resulted in no statistical difference between the 7D spacing and the 8D spacing even though the 8D spacing demonstrated a trend to produce higher values. All spacings used an end distance of 7D which is the minimum dictated by NDS. The lack of difference between the 7D and 8D spacing may be due to the end distance being over loaded and the connection failing from the end of the specimen.

Table 5.1: Results for Optimal Spacing for Seven Parameters.

	Expected Yield Mode II	Expected Yield Mode III	Expected Yield Mode IV
Maximum Load	7D	6D	N.I.
Failure Load	7D	N.I.	N.I.
E.E.P. Yield Load	7D	6D	7D
5% Offset Load	6D	6D	N.I.
Elastic Stiffness	N.I.	N.I.	N.I.
E.E.P. Energy	7D	7D	7D
Ductility Ratio	N.I.	N.I.	N.I.

N.I.: No inference can be determined.

The final objective was to generate data to enhance the model produced by Heine (2001) to predict behavior of multiple-bolt connections. All data for the monotonic and cyclic tests can be found in Appendices A and B.

5.2.1 Yield Mode Predictions

Further investigation is needed to determine why the Yield Limit Model did not accurately predict the yielding behavior of the connections. Many variables appear to be affecting the model's predictions such as the number of bolts, the type of loading, the wood material, the bolt strength, and the diameter of the bolt. The NDS recommended values for dowel bearing strength and bolt yield strength were not similar to the actual values measured in this research. Therefore, the Yield Mode Theory did not accurately predict yielding behavior. It is strongly recommended for future research that actual samples of the testing materials be tested so more accurate values for dowel bearing strength and bolt yielding strength can be used in yield mode prediction calculations. It is also recommended that a few initial tests are performed of any connections to ensure that the predicted yield mode is actually being obtained.

5.3 Limitations of Research

Limitations of research include the following:

- Only single-shear connections were tested.
- Only five alternative spacings were examined (3D, 5D, 6D, 7D, 8D).
- Only two species of wood material was used (Southern Yellow Pine and Mixed Southern Yellow Pine).

- Only timber with a small range of moisture contents was examined.
- Only a single row of bolts was tested.
- Only connections utilizing five bolts were tested.
- Only loading parallel to grain was performed.

5.4 Recommendations for Future Research

To expand this research, future research could include retesting the connection configuration that the Yield Mode Theory predicted would result in Yield Mode III yielding because the timber material used in this research was found to be significantly lower in specific gravity than the value given by NDS. Recommendations include testing the timber material initially to assure that higher specific gravity values are present. Also, the connection configuration could be initially tested to assure that Yield Mode III will result because alternate tests in this research showed that the Yield Mode Theory does not accurately predict the type of yielding that actually occurs when five bolts are present. The tested spacings should be limited to 7D, 6D, and 5D based on results from this research. Testing for Yield Mode IV could also be performed because the yielding behavior was not present in the connection configuration that was tested in this research. Because Anderson (2002) obtained some Yield Mode IV behavior in a connection utilizing three bolts in a single row connecting two 4x6 Southern Yellow Pine lumber, this connection layout is recommended. The tested spacings should be limited to 7D, 6D, and 5D based on results from this research.

To calculate the yield strength of the bolts used in this research, bending tests were performed. Future research could test the bolts in tension so the results could be compared to the minimum yield strength values provided by the manufacturer. The tension test results may cause the Yield Mode Theory to change in the yield prediction. Other research could be performed to improve the Yield Mode Theory so that the theory more accurately predicts the type of yielding that occurs in multiple-bolt connections. Testing could also be performed to aid in the expansion of the Yield Mode Theory to account for capacity design and failure mechanisms. Additional research could be performed on multiple-shear connections and on connections with multiple rows of bolts to investigate the effects of spacing so a deeper understanding of multiple-bolt connections subjected to reverse cyclic loading is obtained.