

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

### 6.1 Conclusions

The results of this work have added to the relatively small amount of information that previously existed for lag screw connections. Results from this study consist of complete lag screw connection load-slip curves with quantified load and slip values, including capacity and 5% offset yield load resistances of lag screw connections for materials that are presently used in construction, and results from dowel embedment, moisture content, specific gravity, fracture, tension strength perpendicular-to-grain, and inked lag screw connection tests. All of these methods were considered in this project due to their probable impact on facilitating the development of lateral load prediction equations that incorporate the variables of pilot hole diameter and lag screw diameter. The results of the studies, both experimental and analytical, are presented in this section.

1. Both Douglas-fir and spruce-pine-fir connection specimens used in the study had similar values for specific gravity.
2. If actual embedment and dowel bending strengths in the determination of the unfactored design lateral load, the difference between experimental and predicted loads is significant.
3. Laterally loaded lag screw connections apply perpendicular-to-grain loading on the main member at preexisting cracks, thereby significantly affecting the load resistances of connections in a negative way. This effect was quantified and used in combination with a mechanical method of modeling the lateral component of withdrawal resistance.
4. It was observed that lateral resistance for lag screw connections could be predicted when given the species, lag screw diameter and pilot hole diameter. It was determined that connections with pilot holes smaller than those specified in the *NDS*<sup>®</sup> had significantly lower lateral resistances than those with pilot holes that were in compliance to the *NDS*<sup>®</sup> standard. Connection

resistance formulas for 5% offset yield, capacity and their respective design resistances were developed, which predicted lateral resistance based on pilot hole diameter, lag screw diameter, and also crack profile surface area and exposed crack length.

5. Pilot holes have a significant effect upon lag screw connections, particularly for lag screws larger than 1/4 in. diameter. When compared to other groups of 1/4 in. lag screw connections, connections with 1/4 in. lag screws did not appear to be sensitive to the pilot hole to lag screw diameter ratio, as no significant reduction in load was observed.
6. Connections with larger than 1/4 in. diameters lag screws will benefit from the work in that a clearer understanding of load resistance reserves may now be quantified subsequent to significant wood cracking. The larger the lag screw diameter, the greater the pilot hole effect.
7. Experimental design lateral resistances were only about 10% greater than results obtained from stipulated *NDS*<sup>®</sup> general dowel equations. More specifically, the *LRFD*-based methodology is conservative, as the experimental nominal design lateral resistances were a minimum of twice that presently used for lag screw connections.
8. To adequately explain the cracking phenomenon, two effective loads were quantified. The two components to the overall effective load are for (1) creation of crack profiles (surface energy) and (2) crack profile separation (remaining strain energy). It was determined that shear contributes significantly to the deflection and prying of the wood being separated at the lag screw location.
9. It was concluded that end and edge distances and spacing contribute significantly to the structural adequacy of the lag screw connection, as well as any other wood connection. Edge and end distances and spacing for lag screws is in need of further consideration, particularly when non-complying pilot holes are used in connections.

10. Specifications regarding lag screw quality and fabrication and assembly (Section 9.1 of the *NDS*<sup>®</sup>) are in need of a more simplistic, yet still conservative, approach.

## 6.2 Recommendations

From the experimentation and analytical work undertaken for this project, many recommendations were made. These recommendations are listed in this section.

1. An overall correction factor for lag screw connections should, as a minimum, include such variables as specific gravity, lag screw diameter and predrilled hole diameter. In such cases, when prescribed pilot holes were not used in lag screw connections, the load resistance, based on an *NDS*<sup>®</sup> pilot hole, should be multiplied by reduction factors.
2. Intermember friction and friction between the lag screw and the wood, which was not accounted for in the models, should be evaluated in latter research.
3. It is recommended that all connections use *NDS*<sup>®</sup> specified pilot hole diameters.
4. However, if these specified pilot holes are not used, a reduction of the allowable design resistance is required. The only exception is for 1/4 in. and smaller diameter lag screws, as pilot hole diameters have no significant effect on connection resistance.
5. Resistance factors should be increased or lag factors decreased value due to over predicted resistance values. Also, a decreased value for  $n$  may be considered.
6. In the event that pilot hole diameters, smaller than those specified in the *NDS*<sup>®</sup>, are to be used in a construction project, spacing between multiple lag screws should be increased to a value much greater than the present requirement of 4D. Under the same conditions, increased end and edge distances were recommended.

7. Noncompliance to standards set by the *NDS*<sup>®</sup> calls for increased safety considerations; otherwise, a decrease in lateral load carrying ability is expected for lag screw connections using lag screw diameters greater than 1/4 in.
8. The pilot hole requirement should not apply to 1/4 in. lag screws connections.
9. Connections with greater than 1/4 in. lag screws should use pilot holes with diameters equal to 75% of the lag screws' nominal diameter. Soaping or the use of lubricant should not be required for lag screws that comply to this recommendation.
10. More work is necessary to determine consistent mechanical and dimensional properties of lag screws. A screw with no shank (fully threaded) would be one way to control the length of the threaded portion.

### **6.3 Yield Theory, *NDS*<sup>®</sup>, *TR-12*, and *LRFD***

Because Yield Theory does not account for instances of cracking, among other things, it follows that modifications to the present Yield Model are recommended. Once adjustment factors were accounted for, at the design level, Yield Models from *NDS*<sup>®</sup> and *TR-12* fairly well predicted experimental 5% offset yield lateral resistances for connections that used *NDS*<sup>®</sup> prescribed pilot holes. However, capacity design resistance using the *LRFD* requirements was not predicted well, based on a connection complying to the *NDS*<sup>®</sup> pilot hole requirement. With respect to this project, the correction factor should, as a minimum, include such variables as specific gravity, lag screw diameter and predrilled hole diameter. When prescribed pilot holes were not used varying amounts of decreased load resistance occurred. In such cases, the load resistance, based on an *NDS*<sup>®</sup> pilot hole, should be multiplied by reduction factors. Reduction factors were included in the “*Analytical Results and Discussion*” chapter. By following the above methodology, the bridge between Yield Theory, the *NDS*<sup>®</sup>, *TR-12*, and *LRFD* may be strengthened.

## 6.4 Limitations of Research

This research was in no way intended to provide answers to the many circumstances that affect the lateral load carrying ability of lag screw connections. However, this testing program added much new information to wood engineering knowledge that existed prior to the publication of this work. Limitations do exist. Many of the following limitations are contained in Section 5.2.6 of this work.

1. Fastener edge and end distance contributed with respect to the amount of wood cracking/splitting and resulting load resistance. Differences in edge and end distances will exist for other connections. Some adverse effects may occur due to using smaller edge and/or end distances.
2. Connection fabrication could not be performed equally for all specimens, as there were likely small differences between specimens. As a result, connection geometry was slightly different from one specimen to another.
3. Main member specimens were inherently variable, because wood is a highly variable material. As a result, material and geometric properties were variable. Also, the species of wood were limited to Douglas-fir and spruce-pine-fir.
4. Tests were performed in an engineering laboratory. Such conditions do not replicate actual in-service conditions with respect to environmental, construction and loading factors.
5. Only certain diameters of lag screws were used with a single length. However, many different and varied lag screw sizes are used today.
6. Material properties used were specific to the lag screws and wood used.
7. Oversized holes were used in the steel side plates. Different diameters of holes may possibly be used by contractors, which would tend to increase or decrease the amount of lag screw head fixity at the steel plate.
8. Though wood main members were subjected to periods of conditioning and relaxation, these conditions will be varied for connection end-use. Dimensional changes due to shrinkage and swelling must also be considered,

particularly because they tend to influence load resistance (embedment strength) and lag screw head fixity.

9. Friction between the side member and main member were not considered in the analysis. Increased lag screw head fixity will increase intermember friction. Friction is difficult to quantify due to the inability to measure the induced compression load between the two members. Upon advanced stages of wood relaxation around the fastener or wood shrinkage, the compression resistance between members will likely decrease, thereby making the task of quantifying friction much more difficult. *TR-12* (AF&PA, 1999) conservatively ignores frictional effects, by equating it to zero.
10. For main members nominal 2 x 6 x 14 in. long were used. Fasteners were screwed into the thickness-length plane (2x14 plane). As a result, test results are limited, in part, to nominal 2x members.
11. Total test time was between five and seven minutes in duration. For such a duration of load application, the load duration factor is between 1.6 to 1.65, but closer to 1.6. End-use load duration may be anywhere from zero to infinity minutes. Therefore, the load duration factor may range from 0.9 for permanent loading to 2.0 for impact loading.
12. Main members were not pressure-treated with water-borne preservatives of fire retardant chemicals. Using such treatments in-service may require a reduction in the load duration factor. Additionally other adjustment factors may be required depending on environmental, construction, and loading conditions ( $C_M$ ,  $C_t$ ,  $C_d$ , and  $C_{eg}$ ).
13. Pilot holes may be used that are of different diameter than those used in this study. Small adjustments may be necessary as the regression used to obtain the reduction factors did not consider these pilot hole diameters.
14. Penetration of the lag screws into the main member was consistently 2.75 in. Because many fastener lengths exist, different penetrations are possible. Yield Theory is based on a minimum penetration to shank diameter ratio of 4.0. Penetration to shank diameter ratios less than four are prohibited, while

ratios greater than 4.0, but less than or equal to 8.0, tend to increase the lateral resistance capacity of the connection.

15. Moisture contents for connection specimens and specimens for the other tests ranged between 11% and 15%. Moisture content value for end-use conditions will vary widely.
16. Connection specimens were tested in single shear. Connection specimens subject to double shear were not considered in this work.

### **6.5 Recommendations for Future Research**

Though, this investigation added much information to the existing library of information for laterally loaded lag screw connections, it by no means is to be considered all encompassing. Additional information is required before lag screw connections can be more fully understood. The following list is provided as a means of enumerating some of the primary areas where additional studies may be required:

- Research to more adequately determine available lag screw material and geometric properties, including shank and root diameters and shank and threaded portion lengths
- Research to conduct lateral load tests on lag screw connections comprised of many variables, including wood species/specific gravity, moisture content, lag screw length and diameter, lag screw shank and threaded portion lengths, pilot hole diameter, and loading rate
- Research for the development of fracture mechanics and a mathematical model used to predict lateral load resistance for lag screw connections, in which wood is modeled as an anisotropic or orthotropic material, instead of an idealized isotropic material
- Research with finite element modeling to develop models for predicted lateral load resistance for lag screw connections

## 6.6 Transfer of Technology

The achieved results can be implemented in a manner to alter design specifications for wood construction. By doing this, lag screws may be installed with various sizes of pilot holes for connections that use 1/4 in. 3/8 in. or 1/2 in. diameter lag screws. Because pilot holes are not used in many cases where they are applicable, it will be of benefit to the forest products industry to have such provisions added to design specifications. In the face of pre-existing cracks, the results allow lag screw connections to be designed with more confidence. Of great importance in the transfer of this new knowledge, regarding lag screw connections, is that it will provide assistance to the manufactured housing industry in improving the safety of housing and maintaining the affordability of housing in the fastest growing sector of the housing industry.

This project's results will be transferred to the timber design community by the future publication of technical journal papers and manuscripts, proposals for change to the *NDS*<sup>®</sup> and *LRFD Specifications for Wood Construction*, research reports posted on a web site, and presentations at technical conferences.