1.0 INTRODUCTION

When the best strength characteristics of wood, such as compression and tension parallel-to-grain, are incorporated into the design of connections, the greatest hazard towards the achievement of connection efficiency is typically sidestepped. In this case, wood is nearly twice as efficient as structural steel with regard to strength to weight ratio (Rodd, 1999). In the presence of shear parallel-to-grain or tension perpendicular-to-grain stresses, this advantage vanishes, as wood is considered a brittle or quasi-brittle material, and the use of wood in this condition is tenuous at best. This overriding weakness is usually manifested with the presence of cracks. Hence, in an effort to control connection cracking/splitting, the goal of good timber design practice is to minimize the weaker strength characteristics and maximize the stronger strength characteristics. Many of today's wood connections, comprised of single or multiple fasteners, are subjected to tension perpendicular-to-grain loads and stresses. Because perpendicular-to-grain stresses in wood connections are indiscriminant as to fastener type, it does not matter whether the fasteners are bolts, nails, drift pins, wood screws or lag screws.

Current wood connection design codes, used by the varied countries of the world, use data based on single fastener experimentation, such as with lag screws. Single dowel connections tend to be more ductile in their behavior than multiple dowel connections. Multiple dowel connection design should therefore be adjusted to account for this compounding effect. Connections using multiple lag screws also display this behavior. However, prior to understanding connections with multiple lag screws, single lag screw connection tests should be performed, and associated results fully comprehended and disseminated. Lag screws (commonly called lag bolts) have been used extensively in the construction industry as well as manufactured housing industry. Typically lag screws are used to connect wood plates or relatively thin steel plates to thicker wood main members. Lag screws are used for both applications of withdrawal resistance and lateral load resistance, while bolts are used primarily to resist only lateral loads.

In the manufactured housing industry, one of the principle uses of lag screws is the connection of the wood-frame house to the transportation chassis. In this particular application, the 3/8-inch (sometimes 1/4 in.) diameter lag screws are typically installed without the *National Design Specification for Wood Construction* (*NDS*®) (AF&PA, 1997) prescribed pilot (lead) holes. Though this practice first appears to be without consideration to structural principles, there is appreciable cost savings involved with this process. The question is then deflected to the quality and safety of manufactured housing.

During the 1990s, a few manufactured homes separated from the chassis during transport, thereby causing accidents resulting in injury. Upon further investigation, it was determined that a large percentage of the houses attached to the chassis showed splitting of the wood surrounding the screws. Splitting of wood is tied to the pilot hole diameter drilled in the wood main member prior to application of external lateral and/or withdrawal loading. Such conditions are also seen in many applications of lag screw connections, including member-to-member attachment and steel strap to wood framing connections. Though this work primarily considers the combination of lag screw and pilot hole diameters, the on-going case study regarding the manufactured housing industry and its use of lag screw connections with no pilot holes is of great interest.

To address the splitting issue respective to manufactured housing, the Department of Housing and Urban Development (HUD), the regulatory agency for manufactured housing, issued a ruling requiring the use of pilot holes for lag screw connections in accordance with the *NDS*® (AF&PA, 1997) requirements; however, the industry protested this ruling, claiming the additional cost associated with the requirement was not justified and would unnecessarily raise the cost of manufactured homes. The foundation of the protest was that the pilot hole guidelines had little experimental or rational basis, and even when the guidelines for pilot hole size were followed, splitting often occurred. Based on this protest, HUD placed a hold on the ruling until further research was conducted to determine a rational basis for installation of lag screws or to quantify the effect of wood splitting on the behavior of lag screw connections. This results in a continuation of the practice of house attachment to chassis in a manner that violates the *NDS*® requirements, and a significant risk of additional accidents is placed on the public.

Subsequent to occupancy of the house, but after transporting the house to its final destination, and due to wood splitting, another problem with this practice is the reduced capacity of lag screw connections. This negatively influences the ability of manufactured homes to resist wind loads and have a positively (uninterrupted) connected load path to the foundation, in which to transfer the loads. The weakest link of the load path controls the structure's capability to handle externally applied loads, such as wind or earthquake; thus, cracked or split lag screw connections could likely be the controlling structural limitation for the manufactured house.

While lag screws have been used extensively and successfully as fasteners for wood construction, guidelines with respect to size of pilot hole, spacing, end distance, and edge distance are predominately based on relatively few experimental tests and judgment related to bolted connections, rather than a rational basis for lag screws. Guidelines for pilot hole size (40 to 70 percent of the diameter of the screw sizes used for this investigation) provided by the *NDS*® (AF&PA, 1997) are intended to minimize splitting of the wood surrounding the screw; as such, design values assume minimal or no splitting of the wood surrounding the screw. Over the years, these guidelines have generally provided acceptable performance of connections using lag screws; however, there currently does not exist the capability to predict lag screw performance when the wood is split around the screw due to insufficient pilot hole diameter or other causes. Results that are obtained from connection tests will also provide additional information for determining spacing, end distance, and edge distance requirements for lag screw connections.

The rationale of today's lag screw connection design is based on Yield Theory; however, the theory has limitations, which are presented in the "Literature Review" chapter. One of the primary limitations is that the model assumes the connection does not fracture due to perpendicular-to-grain tension or shear stresses. Because cracking, to some extent, occurs in most lag screw connections, one of the theory's assumptions is violated. It is therefore imperative that another model be developed, which may include many of the aspects of Yield Theory, but also accounts for the cracking process. Additionally, at present, though load and resistance factor design (*LRFD*) addresses deflection for members, slip is not explicitly mentioned for joints, and, hence brittle failure remains a concern (ASCE, 1996; Smith and Foliente, 2002).

Due to insufficient pilot hole diameter, cycling of moisture and seasoning effects, and in-service loads, cracking in lag connections can easily occur. Propagation of cracks further weakens the connection. To adequately design connections and account for these variables, a possible remedy is a fracture mechanics model. By developing such a model, lag screw connections can be designed such that the design loads are kept well below the 5% offset yield load or capacity (ultimate load) depending on the desired margin of safety. For simplicity, Linear Elastic Fracture Mechanics (LEFM) was studies in the hopes of developing an isotropic approximation for the lag screw connection. By testing and modeling single lag screw connections and monitoring the resulting crack length from zero to failure load, it is possible to estimate the remaining capacity based on load history. Secondly, the knowledge derived from testing single lag screw connections with measurement of preliminary cracks, will help facilitate the rationalization of end distance and spacing requirements for multiple lag screws joints. Field investigations will also benefit by results achieved from the research: an investigator will be able to estimate the amount of resistance (5% offset yield load or capacity) remaining in a cracked connection. However, in the process of making a structural system more efficient, the redundancy is somewhat compromised.

The objective of the experimental and analytical work for this study is to develop a methodology to predict the load-slip performance of lag screw connections that experience wood splitting (in terms of 5% offset yield design loads and capacity), quantify the available lateral resistance of lag screw connections installed with various pilot hole diameters, and develop a method of predicting lateral resistance based on lag screw diameter and pilot hole diameter. The research attempted to blend concepts of fracture mechanics and mechanics-based modeling, in addition to experimental results, to develop a mathematical model that predicts the available lateral resistance of lag screw connections, including the effects of wood splitting.

Additionally, to adequately explain the cracking phenomenon, two effective loads had to be developed: one for the creation of crack profiles (surface energy), and the other for crack profile separation (remaining strain energy). By implementation of the engineering mechanics analysis and experimental tests (inked tests and fracture tests), these theoretical effective loads were determined.

One of the objectives of this project was to derive lateral design resistance values for cases of lag screws with no pilot holes or small pilot holes, presently prohibited by AF&PA's publication, *NDS® National Design Specification for Wood Construction* (AF&PA, 1997). A reduction in capacity and 5% offset yield load was observed, due to the absence of pilot holes or use of smaller pilot holes than prescribed. However, it will be of great benefit to the manufactured housing industry by allowing an option of using lower design values for the case of no pilot holes, using *NDS®* required pilot holes, or developing self-drilling lag screws. The results of the research will improve the understanding of variables that affect lag screw performance, and provide a rational methodology to account for the effect of splitting of wood around lag screws. This information 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. Additionally wood structures other then manufactured houses will benefit from the research, as in many cases lag screws are implemented to attach wood-to-wood and steel-to-wood in construction applications.