RESIDENTIAL BUILDING MATERIAL REUSE IN SUSTAINABLE CONSTRUCTION

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Most importantly, I thank Jen, Remy, Sunshine, and even Oliver for their love, support, and for picking me up, dusting me off, and pushing me forward on countless occasions.
RESIDENTIAL BUILDING MATERIAL REUSE IN SUSTAINABLE CONSTRUCTION

Abstract

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Social concerns about resource utilization and energy consumption have resulted in an expanding view of our common sustainable future, one that is being shaped by a growing need to improve environmental performance with an eye toward the economy. The role of residential deconstruction in reuse and recycling was examined within the broader context of material and energy conservation in sustainable development. The life cycle of residential building products was examined to identify potentially high impact opportunities to address sustainability.

Extending the service life of building materials through reuse presents an opportunity to address sustainable development through reducing material and energy demands. To extend the service life of building products it is necessary to understand the current use and service life of materials used in structures. Additionally it is apparent that the application of design for deconstruction concepts combined with a fastening methodology that enables deconstruction while reducing design event and deconstruction damage is required. The use of hollow fasteners may satisfy the requirements of a fastening system that reduces damage in the connected materials. The objectives of this research were to predict the service life of building materials
and to develop an understanding of the behavioral characteristics of joints connected with hollow fasteners.

Housing inventory data obtained from U.S. census housing surveys was used to build housing age distributions. Weibull and Gompertz curves were fit to the distributions and used to predict service life. The service life of residential structures was estimated as 99 to 110 years.

To characterize hollow fastener behavior, fasteners were subjected to shear loading in test fixtures and in lap-joints. Regression techniques were used to model hollow fastener behavior as impacted by fastener diameter and wall thickness. A displaced volume method in combination with dowel bearing test results was used to model laminated strand lumber (LSL) deformation under loaded fasteners. It was found that bearing material damage can be decreased when joint yield results from fastener buckling. Through application of the models, LSL lap-joints can be designed such that the primary mode of initial joint yield is due to deformation in the hollow fasteners.
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Dedication

This dissertation is dedicated to H. Michael & Mildred Bartlett, Carl & Phyllis Olson, Dermott Kavanagh, Drifter, and Sunshine, all of whom left cherished memories with the author.
CHAPTER ONE

Project Introduction

Introduction

Infrastructure construction, use, and maintenance have been estimated to account for about 40% of total U.S. energy consumption (Watson, 1979). Social concerns about resource utilization, energy consumption, carbon emissions, and indoor air quality are currently being addressed in the U.S. by a rapidly growing green building movement (Kibert, 2003a). Green building codes have emerged for the purpose of promoting occupant health, resource efficiency, and minimizing the impact of the built environment on the natural environment (Kibert, 2003a), thus new requirements for structures and building products are evolving. We are now faced with an expanding view of our common sustainable future, one that is being shaped by a growing need to improve environmental performance with an eye toward the economy.

Sustainable Development and Green Building

Social concerns about resource utilization, energy consumption, carbon emissions, and indoor air quality have led to the creation of green building codes. While improvements in energy and water use in nonresidential buildings were the initial focus of the green building codes, the codes have been expanded to incorporate provisions addressing the use of environmentally friendly building products and indoor air quality concerns as well. Similar to how concerns regarding forestry practices ultimately led to a market for certified forest products,
social demands for energy efficiency, utilization of environmentally friendly building products, and improvements in indoor air quality have begun to reshape building product offerings as some product lines have been designed to provide product attributes, such as recycled content, that are compatible with the provisions in the green building codes.

Green building codes such as Leadership in Energy and Environmental Design (LEED; USGBC, 2008) and material certification programs such as the Forest Stewardship Council (FSC) ratings came into existence through market demands and voluntary compliance. The growth of green building codes and material certifications are related to program awareness and to the spread of the social values and philosophies that resulted in their creation. Advancement toward sustainable design is likely to create growth in demand for building products that satisfy the requirements of the green building codes.

It appears that the impetus for sustainable development is growing and will result in broader engagement that will accelerate the adoption of values and practices geared toward advancing sustainable development. Bernstein and Bowerbank (2008) claim that 94% of current architectural and engineering firms expect to be significantly involved with green building projects by 2013. Social demands for energy security, decreased environmental damage, and reduction in carbon emissions have already begun to change building product needs and requirements. Accelerating the advancement of sustainable development has the potential to reshape economic models and further alter the future needs and requirements of building products.
Design Trends

Social demands for environmentally friendly building products and reduced energy consumption are not the only factors prompting changes in building product requirements and construction methods. The desire to minimize capital costs associated with long construction times has fueled development of rapid construction techniques. Modular construction methods provide a means to reduce construction times as modules are more efficiently mass-produced on factory floors than they are on a construction site (Olson, 2010). Assembly of a final structure is facilitated on site by simply connecting modules together. In the case of residential construction, Redman Homes has used modular construction concepts to decrease their schedule from order to on-site installation from four months to eight weeks (Kim, 2008). Cameron and DiCarlo (2007) highlight that modular construction financially outperforms conventional construction by 5% to 15% due, in part, to less loan interest resulting from shorter construction times.

In addition to reduced capital costs, modular construction has been attributed with yielding residential structures that are more energy efficient than those built using conventional methods. Olson (2010) states that due to factory conditions and improved oversight, modular homes are of higher quality. Kim (2008) points out that modular homes are 80% more airtight than those produced using conventional methods due to higher quality standards associated with factory assembly methods.

While modular construction currently accounts for a small portion of national housing market, it is increasing in popularity. Figure 1.1 shows the growth in modular construction since 1996.
Timber Building Materials

Efficiency of the Forest Products Industry

Building products derived from forest resources have typically been a major component of housing built by conventional means. Winnandy (2006) states that in North America, over 40% of the total materials used in residential construction are wood-based building products. The trends in modular construction are still heavily reliant on wood-based building materials. As forest resources are renewable, forest products are commonly associated with the green building and sustainable development. Lippke et al. (2004) have performed life cycle assessments focused on forest products that have shown that wood-based building products often have lower environmental burdens and embodied energies than other alternatives. Even though forest products are generally considered environmentally friendly with regards to production and use, there is room to further improve their environmental impact through expanded reuse and recycling.

Figure 1.1. Modular construction market growth (Olson, 2010).
The Circular Product Life Cycle

Traditionally, wood building materials used in structures have been removed from service through demolition and then disposed of in a landfill or through incineration. Thus, the life cycle for most building materials has been characterized by a single application followed by disposal (Crowther, 1999). The traditional product life cycle is shown in Figure 1.2 and is characterized by the sequential steps of 1. resource extraction and acquisition, 2. product manufacture, 3. distribution, 4. Conversion or use, 5. disposal. The linear life cycle limits product and material service life to a single life or application and results in relatively high levels of waste production (Crowther, 1999).

![Figure 1.2. Linear life cycle for building products.](image)

Crowther (2001) stated that one of the major strategies to reducing the environmental impact of a product is to alter the single use and discard cycle to incorporate reuse and recycling. Opportunities for carbon sequestration, material conservation, embodied energy conservation, decreased demand for landfill space, and advancement toward sustainable development lie in transitioning residential building products from a linear life cycle to a circular life cycle. A circular life cycle is shown in Figure 1.3 and is characterized by: resource extraction, resource acquisition by a manufacturing facility, conversion of the resources to building products, distribution of the building products, use of the building products in a structure, reuse which takes building products and re-inserts them into the life cycle just prior to use, component recycling which takes product components and re-inserts them into the life cycle at the
production and manufacturing stage, material recycling which takes materials and re-inserts them into the life cycle at the raw material acquisition stage, and finally disposal in a landfill or through incineration which takes the products and materials out of the circular pattern and terminates the life cycle. Incorporating reuse and recycling into the residential building material life cycle assumes that there are useful materials remaining at the end of a structure’s service life.

Figure 1.3. Circular life cycle for building products (adapted from United Nations Environmental Programme, 2010).

While some structures are lost due to damage from catastrophic events, not all residential structures are demolished due to loss of structural integrity. Johnstone (2001) states that few
dwellings are demolished due to a failure of the structural system and that the potential service life of most residential structures is not realized. Johnstone (2001) and Bender (1979) attribute residential structure loss to economic decisions where alternate use of the structure or land on which the structure is situated favor demolition over continued use of the structure. Additionally, several studies examining housing mortality have found that the loss of residential structures is non-linear with time and that losses occur across all age classes of the housing stock (Bradley & Kohler, 2007; Gleeson, 1981; Gleeson, 1985). An example of early housing loss appears in *Los Angeles Times* in May 2009, where it was reported that several new residential structures in Victorville, California, some of which were yet to be completed, were demolished because the bank deemed the investment in their construction unrecoverable due to the collapse of the real estate market in California (Hong, 2009). In Detroit, Michigan, and Youngstown, Ohio, population loss due to migration created an oversupply of housing resulting in housing abandonment and urban blight which in turn sparked discussions of residential demolition (Hiltzik, 2010). As in Detroit, industrial decline in Flint, Michigan, led to an oversupply of housing, which contributed to demolition of residential structures (Basset et al., 2006).

Residential buildings removed from the inventory for economic reasons contain materials that have not reached their potential service lives. Certainly a portion of these building materials would retain sufficient residual strength and service life to provide satisfactory service in other structures through reuse and recycling.

**Hierarchy of Reuse and Recycling**

There are a few general scenarios that capture the end-of-life options for any given product or material. In describing recycling and reuse, Young (1995) discussed a “3Rs” model
to reducing life cycle energy consumption. He defined the three Rs as reuse, remanufacturing, and recycling where:

- **Reuse** is a product being used more than one time for its intended purpose,
- **Remanufacturing** is a product being disassembled into its constituent components that are then reused to assemble new products, and
- **Recycling** is the collection of products that are separated into their base materials that are then reused as raw materials in the production of other products.

Young points out that certain end-of-life scenarios are more environmentally desirable than others. From the perspective of production energy conservation, Young notes that reuse is preferable to remanufacturing, which is preferable to recycling. Crowther (2001) expands and redefines the recycling hierarchy to consist of building reuse, component reuse, material reuse, and material recycling where:

- **Building reuse** refers to the relocation or reuse of an entire building. An example of this is the Cellophane House commissioned by The Museum of Modern Art in New York City and designed by KieranTimberlake. The Cellophane House is a modular dwelling designed to be assembled, used, disassembled, moved, and re-assembled to provide the same function in a different location (KieranTimberlake, 2011).
- **Component reuse** is the reuse of building components in a new building or elsewhere in the same building. An example of component reuse would be removing a wooden roof truss from one building and reusing it as a roof truss in another building.
- **Material reuse** is the reprocessing of used materials into new components. An example of material reuse would be the disassembly of a wooden roof truss removed from a building and machining the wood components of the truss to produce wood flooring.
• *Material recycling* refers to the recycling of resources to make new materials. An example of this would be removing wood flooring from a building and then using it as a raw material to produce particleboard.

As with Young’s hierarchy of reuse and recycling, Crowther’s is organized from the highest to lowest order use. Downcycling, which is defined as “the process of reducing a raw material’s quality, potential for future uses, and economic value” by Chini and Bruening (2003), is left as a last option. Following the recycling hierarchy and avoiding downcycling to the extent possible may minimize processing energy expended in product manufacture as well as maximize the retention time of raw material mass in the built environment. The recycling hierarchy, graphically shown in Figure 1.4, has been expanded to include disposal. Disposal as used here consists of landfilling and/or incineration.

![Figure 1.4. Reuse, recycle, and disposal hierarchy.](image)

Reuse and recycling represent opportunities to reduce virgin raw material demands associated with construction activities (Guy & Shell, 2002). Additionally, reuse and recycling provide a means to lower the embodied energies in structures through the extension of material service life (Thormark, 2002; Kibert, 2003b) and, in the case of cellulosic building products, to increase the duration of time that carbon is retained in the built environment. Reuse provides an opportunity to keep products and materials in service with minimal reprocessing. While reuse
and recycling represent opportunities to reduce environmental impacts and to reduce energy, only limited amounts of reuse and recycling of building materials has developed (Webster & Napier, 2003; Leigh & Patterson, 2006). One of the problems inhibiting reuse and recycling of building materials is the design and construction method. Current construction methods employ permanent fixing methods and are not designed to be deconstructed (Crowther, 2001; Guy & Shell, 2002).

**Waste Stream Disposition**

Construction and demolition (C&D) waste is often separated for the purpose of recovering and recycling useful materials and for disposal in C&D waste specific landfills. Portions of the C&D waste stream, such as scrap steel and wood, have the highest recovery rates of building materials (Chini, 2007). The wood category of C&D waste generally includes solid lumber, solid beams, laminated beams, plywood, oriented strand board, medium density fiberboard, particleboard, and composite I-beams. Markets trading in recovered heavy timber beams, laminated beams, and lumber for non-structural uses have begun to develop (Hiramatsu et al., 2002; Chini, 2007; Falk & McKeever, 2004). Chini (2007) stated that recovered structural timbers are in high demand because of their lack of availability from other sources. Further, he indicates that a market for used dimension lumber is developing but is hindered by a lack of standard grading guidelines. Falk et al. (2008) embarked on an effort to determine the residual mechanical properties of reclaimed Douglas-fir lumber for the express purpose of facilitating the development of grading guidelines for recovered lumber.

While some solid wood is recovered and reused, the primary path for recovered wood waste is through downcycling. Falk and McKeever (2004) stated the markets for recovered
wood are dominated by production of landscaping mulch and waste wood for fuel. Other
downcycle uses for recovered wood are composting bulk agent, sewage sludge bulking medium,
fibers for manufacturing, and animal bedding (Falk & McKeever, 2004; Chini, 2007).

There are several reasons why downcycling of wood recovered from the demolition
waste stream represents the only viable path for reuse and recycling. Most of those reasons
result from building design and the means used to accomplish demolition.

**Barriers to Reuse and Recycling**

Since most structures are not designed to be deconstructed, demolition activities are
commonly undertaken with speed and labor minimization as the major considerations. Often
times heavy equipment such as end loaders and bulldozers are used to raze residential structures
damaging the building components during demolition activities. Due to current construction and
demolition methods, several barriers need to be overcome in order to enable increased reuse and
recycling of building products. Some of these barriers are:

- sorting recovered materials (Crowther, 1999; Hiramatsu et al., 2002; Guy & Shell, 2002;
  Falk & McKeever, 2004),
- contamination (Crowther, 1999; Hiramatsu et al., 2002),
- difficulty in removing contaminants that enter the material streams during use (Crowther,
  1999; Kibert and Languell, 2000),
- minimizing material damage the demolition (Crowther, 1999; Guy & Shell, 2002), and
- unknown structural capacities of recovered materials (Gorgolewski, 2008; Kibert &
  Languell, 2000; Pulaski et al., 2003).
Design for Deconstruction

Many of the barriers to material reuse can be overcome by planning for structure disassembly and material recovery and avoiding constructions that are difficult to disassemble or constructions in which materials contaminate one another (Thormark, 2002; Pulaski et al., 2003; Crowther, 2001; Guy & Shell, 2002). Such planning embodies the concept of design for deconstruction. Calkins (2009) defines design for deconstruction as, “The design of buildings or products to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components, and materials.” In planning for deconstruction and material recovery, some strategies for addressing material reuse barriers can be employed. One such strategy is to simplify the building deconstruction by using modular components.

Growth in modular design and modular construction present an opportunity to employ design for deconstruction concepts to address sustainable construction. Modular construction designed for deconstruction has the potential to greatly reduce the expense and difficulty in sorting materials by eliminating the need to completely disassemble a structure to the individual construction elements since entire modules can be removed intact (Guy & Shell, 2002; Pulaski et al., 2004; Olson, 2010). Modular construction also has the potential to provide a great deal of flexibility for reuse as removed assemblies could potentially be reused with little remanufacturing required if damage to the assembly materials can be minimized (Kieran & Timberlake, 2008; Olson, 2010).

Olson (2010) states that the most critical design consideration when considering deconstruction over demolition is the connections, and he points out that deconstruction is most easily accommodated when relatively few connectors are employed. Thus deconstruction can be facilitated by replacing several small fasteners such as nails with a smaller number of large bolts.
Olson (2010) states “…changing the design philosophy to favor deconstruction results in decreased ductility because large bolts are less likely to fail while the timber is more likely to crush.” Removable fasteners that maintain or improve structure ductility while minimizing material damage resulting from deconstruction and catastrophic design events could help facilitate module reuse.

**Hollow Fasteners**

The use of hollow fasteners that can absorb energy through deformation in the fastener walls may provide a means to reduce material damage and maintain structure ductility. While little work has been published on the use of hollow fasteners as a means to enable material reuse, some research has been published regarding the reduction of brittle failure in timber joints through the use of hollow fasteners.

Alleviating brittle failure in timber joints through the use of hollow fasteners can be viewed as a similar problem to minimizing damage in bearing substrates. Brittle failure in timber joints often results from rapid crack growth parallel to the grain (Guan and Rodd, 2001a). Reducing rapid crack growth and brittle failure in timber members can be accomplished by minimizing damage and stress concentrations incurred in the bearing substrates. Several researchers have investigated the use of hollow rivets, also referred to as tube fasteners, hollow fasteners, or hollow dowels as a means to improve ductility and prevent brittle failure in timber joints (Cruz and Ceccotti, 1996; Werner, 1996; Leijten, 1999, 2001; Leijten et al, 2004, 2006; Guan and Rodd, 1997, 2000, 2001a, 2001b; Murty, 2005; Murty et al, 2007, 2008).

Through proper selection of rivet diameter, wall thickness, and material, it may be possible to design a joint in which hollow rivets collapse before the critical stresses are reached.
across a large portion of the bearing substrates. If joint failure is preferentially directed into the fastener, substrate damage due to a design event or deconstruction activities may be reduced leaving the building materials reusable by simply replacing failed fasteners.

**Project Objectives**

The use of hollow fasteners in combination with modular construction design trends integrated with design for deconstruction concepts present a unique opportunity to address sustainable construction through material reuse. In addition to enabling reuse through deconstruction, the use of hollow fasteners may help extend the service life of material in structures that are subjected to catastrophic design events such as earthquakes. By reducing bearing material damage resulting from design events, structure repair could potentially be accomplished through fastener replacement.

There has been little research aimed at facilitating material reuse and structure repair by employing hollow rivets to reduce bearing substrate damage. There is a clear need to develop an understanding of the behavioral characteristics of joints fastened with hollow rivets.

Additionally an understanding of how long building materials are used in structures is necessary to be able to extend the service life. Determining the service life of building materials is critical for designing product properties as well as for estimating future demand and planning for material and energy requirements of future building product manufacture. Knowledge of the service life distribution can be used to design test protocols aimed at characterizing the mechanical condition of building materials in the waste stream relative to the estimated mechanical loadings that the materials would have been subjected to while in use in structures. Lastly, knowledge of the service life is necessary for conducting accurate life cycle assessments.
that can be used for comparing alternatives and making appropriate decisions. The specific objectives within this project are to:

1) Predict the service life of residential structures in the U.S. based on previous models and model fits to housing inventory data and thereby provide an estimate of the service life of difficult to access and replace building materials service.

2) Delineate the mechanical relationships and yield behavior in monotonically loaded LSL lap joints connected with hollow fasteners.

3) Establish a method to design lap-joints such that yield is initiated primarily through fastener buckling.

References


CHAPTER TWO

Estimating Service Life of Residential Structures

Abstract

Extending the service life of building materials through reuse presents an opportunity to address sustainable development through reducing material and energy demands. In order to effectively design materials for extended service lives and reuse, it is necessary to know how long building materials are currently used in structures. Currently, there is a lack of understanding of the service life of modern building materials in structures built using current construction techniques. The objective of this research was to predict the service life of building materials.

This paper provides a prediction of the service life of residential structures in the U.S. based on previous models and model fits to housing inventory data and thereby provides an estimate of the service life of difficult to access and replace building materials. Housing inventory data obtained from U.S. census housing surveys was used to build housing age distributions. Gompertz and Weibull curves were fit to residential housing inventory data published by the U.S. Census Bureau to estimate service life. The average service life of residential structures was predicted to be between 62 and 153 years.
Introduction

Previous work addressing aspects of the life cycle of difficult to access and replace residential building materials has focused on life cycle inventory and life cycle impacts of building materials and their application in model homes. Studies such as those conducted by CORRIM have estimated the embodied energies associated with material production, house construction, maintenance, demolition, and disposal (Perez-Garcia et al., 2005; Kline, 2005; Lippke et al., 2004; Puettmann & Wilson, 2005; Wilson & Dancer, 2005; Winistorfer et al., 2005). Additional work in the areas of waste management and recycling has focused on recycling and reuse of solid wood products recovered from demolition and deconstruction activities (Hiramatsu et al., 2002; Falk, 2002; Falk & McKeever, 2004; Falk et al., 2008).

There is a lack of information regarding the service life of residential building materials and the current practices regarding re-use, recycling, and disposal of those building materials. Determining the service life of building materials is critical for designing product properties as well as for estimating future demand and planning for material and energy requirements of future manufacturing of residential building products. Knowledge of building product service life distribution can be used to design test protocols aimed at characterizing the mechanical condition of the building material waste stream relative to the estimated mechanical loadings that those materials would have been subjected to while in use in residential structures. Lastly, knowledge of the building product service life is necessary for conducting accurate life cycle assessments that can be used for comparing alternatives and making appropriate decisions.

The objective of this research is to estimate the service life residential building materials that are difficult to access and replace. Specifically the service life of residential structures is predicted by employing model fits to housing inventory data. The service life of residential
structures is assumed to be the same as the inaccessible parts and thereby provides an estimate of the service life of the inaccessible building products.

**Service Life**

**Service Life of Residential Building Products**

Few estimations for the difficult to access components of residential structures have been published. The service life of products such as plywood and oriented strand board are sometimes implied by product warranties. The expected service life of OSB has been listed as 25-30 years by the National Association of Homebuilders (NAHB, 2007). The American Plywood Association (APA, 2008a) defined the service life of wood composite sheathing as the lifetime of the structure if the structure is properly designed, constructed, detailed, and maintained. Service life expectations are generally based on accelerated weathering tests and materials testing; however, it is not clear if they actually reflect the actual time in service of sheathing panels used in residential construction. OSB supplier warranties suggest a “guaranteed” service life of 20-25 years (Louisiana-Pacific Corporation, 2009; Huber Engineered Woods, 2009; Ainsworth Corporation, 2009).

Other estimates for the service life of difficult to access building components is often assumed to be the same as that of the structure. The International Organization for Standardization (ISO, 2000) states, “The service life of inaccessible building parts should be the same as the service life of the building.” This work adheres to the view of ISO and uses an estimate of the service life of residential housing as a surrogate for the difficult to access and replace building materials used in the structure.
Service Life of Residential Housing – Stock and Flow Models

Service life determination for residential housing has received attention due to its importance in building and material LCAs, residential economics, and urban planning. In LCAs, embodied energy depreciations and energy use estimations are directly related to the service life of the building. While many LCAs are conducted with service lives set to the assumed design life (Haapio, 2008), some LCA practitioners have estimated residential housing service lives in order to improve the accuracy of their assessments.

For LCAs of residential structures, Winistorfer et al. (2005) used U.S. Census data of housing stocks to obtain an estimate of residential housing average service life. For their estimate, Winistorfer et al. estimated service life by examining the housing inventories for residential structures constructed before 1920 and implied that the average service life would correspond to the time when 50% of the housing constructed before 1920 was removed from the housing inventory. Using this approach and adjusting for the overstatement of young building stock in the housing inventory data, Winistorfer et al. (2005) estimated the average service life of residential housing constructed in the United States before 1920 to likely be in excess of 85 years, though to maintain a conservative approach, they used a service life estimate of 75 years in their calculations.

Johnstone (2001b) constructed a stock and flow model that used a probability of loss function fit to housing mortality data from empirical studies to estimate the housing mortality of New Zealand residential buildings. The stock and flow model used a mass balance type of approach to account for dynamic variable interactions that are dependent on the expansion rate of the housing stock. Johnstone estimated the average service life of New Zealand housing to be between 90 and 130 years.
Skog (2008) used a software model called WOODCARB II to estimate the contribution of harvested wood products in the United States to annual greenhouse gas removals through carbon sequestration. Estimates of the change in the stored carbon reservoir were made by tracking inputs and outputs from the carbon reservoir. The inflow into the carbon reservoir was estimated through historical production and consumption rates of harvested wood products. Outflow from the carbon reservoir was calculated from estimates of lifetimes and associated disposal rates of harvested wood products. To compare and adjust the estimate of total carbon stored in U.S. residential housing in 2001, Skog input the stored carbon estimates from U.S. Census and USDA Forest Service data and mathematically verified the half-life estimates he had used in the model. Using the model validation data and assuming that the half-life approximates an average service life, Skog estimated the average service life of U.S. residential housing built before 1939 to be 78 years, housing built between 1940 to 1959 to be 80 years, housing built between 1960 to 1979 to be 82 years, housing built between 1980 to 1999 to be 84 years, and housing built from 2000 to present to be 86 years.

Service Life of Residential Housing – Life Table Model and Fitted Curves

Gleeson (1981, 1985, and 1986) published several studies about estimating housing mortality. One approach Gleeson (1981) used was to fit an actuarial model of loss to limited housing data. From the Annual Housing Surveys published by the U.S. Census Bureau, Gleeson obtained housing inventory data for the South U.S. census region spanning the time period of 1940 to 1977. He then applied an actuarial model to the data. The model Gleeson applied was an adaptation of a human mortality curve developed by Gompertz. The equation for the modified Gompertz curve is written:
Where:

\[ S_x = t - tp^x \]  

- \( S_x \) = number of housing units surviving to age \( x \)
- \( t \) = total number of housing units in the cohort
- \( p \) = proportion of units lost initially, i.e. the number of units lost during the first accounting period as a proportion of \( t \)
- \( R \) = rate of loss

Gleeson compared the results of the Gompertz curves to the results obtained by applying straight-line estimates and to the actual data obtained from the Annual Housing Surveys. He also performed a sensitivity analysis on the Gompertz curves by changing the choice of years used to fit the model. The sensitivity analysis showed that the Gompertz estimates varied only slightly with the choice of year used to estimate \( p \) and \( R \). The sensitivity analysis did show large impacts in the Gompertz estimates based on the year chosen to define the starting point, \( t \). In the discussion of applying the Gompertz curves to housing mortality, Gleeson conceded that the approach was crude, not theory-based, and that the approach lacked a method of verification. However, he concluded that Gompertz curves better matched the actual data than did the straight line projections, and though crude, application of the Gompertz curves could be useful in modeling housing mortality given appropriate data.

In a subsequent paper, Gleeson (1985) estimated housing mortality of a sample of Indianapolis housing by creating current life tables from demolition statistics and housing inventories obtained from the U.S Census Bureau and through inventory estimates made by the Information Services Agency of Marion County. In creating the life tables, housing mortality was determined from one time period and projected into the future. Due to a lack of data for
very old dwellings, Gleeson applied a Gompertz curve to estimate mortality in residential structures older than 95 years. Using the life table approach, Gleeson estimated the average service life of the sample of Indianapolis residential structures to be 100 years.

In a third study, Gleeson (1986) examined the application of several standard curves to the Indianapolis survivorship data from a previous publication (Gleeson, 1985) as well to a sample of housing inventory data for the survivorship of mobile homes. The curves that Gleeson used in his comparison were a Pearl-Reed curve, a bell curve, a Gompertz curve, an exponential curve, a fitted straight line, and a two-parameter Weibull curve. The straight line and exponential curves were fitted using linear regression while the other curves were fit by nonlinear regression. The percentage of years where the curve predictions were within ten percent of the actual were 49, 100, and 98 for the Gompertz, Pearl-Reed, and Weibull curves respectively. The percentage of years where the curve predictions were within ten percent of the actual were 97, 91, and 100 for the Gompertz, Pearl-Reed, and Weibull curves respectively. Gleeson employed the Kolmogorov-Smirnov statistic to test the goodness of fit of the curves. The goodness of fit analysis failed to reject the hypothesis that the standard curves fit the survivorship curves, at $\alpha = 0.20$, in every instance except for the Gompertz fit to the conventional housing data. In reference to the conventional home data, Gleeson concluded that the Pearl-Reed and Weibull curves provide good fits if 85 years or more of data are available.

Materials and Methods

Data


**Cohort Establishment and Data Extraction**

Three cohorts of housing units constructed in the United States were selected for service life modeling. The three cohorts were defined by the years in which the housing units were constructed: 1970-74, 1975-79, and 1980-84. The Annual Housing Surveys (U.S. Census Bureau, 1975, 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, and 1984) separated “vacant, seasonal, and migratory housing units” from “year round housing units” and tracked the two inventories differently. The “year round housing units” were inventoried by the number of structures built during a range of time whereas the “vacant, seasonal, and migratory housing units” were tracked by the number of structures only. The American Housing Surveys (U.S Census Bureau, 1988, 1989, 1991, 1993, 1995, 1997, 1999, 2002, 2003, 2004, 2006, and 2008) did not separate “vacant, seasonal, and migratory housing units” from “year round housing units.” Furthermore, the American Housing Surveys list the inventory by the number of structures built during discrete ranges of time. In order to diminish the potential impact on data analysis that the different accounting methods applied to the “vacant, seasonal, and migratory housing units” could have, the “vacant, seasonal, and migratory housing units” were distributed and added to the inventories for “year round housing units” individually in the data obtained from the 1973, 1974, 1975, 1976, 1977, 1978, 1979, 1980, 1981, and 1983 Annual Housing Surveys. The “vacant, seasonal, and migratory housing units” were distributed proportionately relative to “year round housing units” across the discrete time intervals for the inventory of “year
round housing units.” For example, in the 1973 Annual Housing Survey data, 25% of all the “year round housing units” were built between 1960-1969, so 25% of the “vacant, seasonal, and migratory housing units” were added to the number of “year round housing units” reported to be built between 1960-1969.

After correcting for the difference in “vacant, seasonal, and migratory housing units,” there was still a readily apparent difference in the inventories before and after 1983. Because of the difference in the inventories, data published in 1983 and before was excluded from determination of the initial cohort sizes and subsequent population changes for the 1970-74 and 1975-79 cohorts. For cohort establishment, the 1970-74 and 1975-79 cohort populations were taken as the values reported for those cohorts in the 1985 American Housing Survey (U.S. Census Bureau, 1988).

Data used for fitting Gompertz curves and the two-parameter Weibull curves was extracted from the data sets that were established as previously described. Data that showed an increase in the housing inventory in years that fell after the establishment of a cohort was excluded from the data sets used for curve fitting.

**Service Life Estimations - Fitting of Gompertz Curves**

Gompertz curves were fit to the three data sets in the manner outlined by Gleeson (1981). Equation 2.1 was used for the curves. The Gompertz curves were fit by first selecting a starting cohort population, \( t \), from the data set. Second, the proportion of units lost initially, \( p \), was determined by subtracting the number of housing units in a subsequent year from the initial cohort population and then dividing that difference by the initial cohort population. The rate of
loss, $R$, was mathematically calculated after selecting a value of $S_x$ and corresponding $x$ from a year after those which were used to determine the constants $t$ and $p$.

**Service Life Estimation - Fitting of the Two-Parameter Weibull Distribution**

Gleeson (1985) found that the two-parameter Weibull distribution provided a good description of the mobile home inventory in Indianapolis. Additionally, the Weibull distribution has been widely used to describe distributions of time to failure for a wide range of devices, materials, and structures (Nakagawa & Osaki, 1975). Because of its wide use in describing time to failure, and specifically because of its past use to describe mobile home inventory distributions, the Weibull distribution was chosen to describe national housing inventory distributions in this work. The cumulative two-parameter Weibull distribution fitted to the housing inventory data is written as follows:

$$F(x) = 1 - e^{-(x/\beta)^\alpha}$$  \hspace{2cm} \text{Eqn. 2.2}

Where:

- $F(x) =$ cumulative probability of a housing unit having a lifespan of $x$
- $\alpha =$ shape parameter
- $\beta =$ scale parameter

The cumulative two-parameter Weibull distribution was the calculated cumulative proportion of housing units lost by age for each cohort. The loss of housing units by age was calculated as a proportion of the total number of housing units in the cohort by dividing the number of units lost over a time period by the initial population of the cohort. Age of the cohort was determined by subtracting the latest year defining the cohort from the year in which the
housing inventory is of interest, e.g. the housing units in the 1970-74 cohort were considered to be 11 years old in 1985.

The variables \( \alpha \) and \( \beta \) were calculated by first estimating their values through a sum of squares data fitting approach. The initial estimates for \( \alpha \) and \( \beta \) were then used as the starting points for an iterative solution process. The iterative solution process was carried out using the NLIN procedure in SAS software.

**Results and Discussion**

Tables 2.1-2.3 contain the actual data and show which data points were used to fit the Gompertz and Weibull models. The Gompertz curves were fit to the first three suitable data points starting with 1985 data. For the 1970-74 and 1980-84 cohorts, the first three data points starting at 1985 were suitable for fitting the Gompertz curves. For the 1975-79 cohort, the 1989 data point could not be used to fit the Gompertz curve because it showed a larger housing inventory than the 1987 data point. The Gompertz curve cannot be fitted with data points that do not show progressive losses. Similarly, the Weibull curves used all of the data points that showed continual losses in years after the establishment of the cohort. The fitting of the Weibull curves used much more of the available data even though several data points were excluded. Because of the model fitting techniques, predictions with the Gompertz model are much more dependent on the first few data points than are the predictions made with the Weibull models.

<table>
<thead>
<tr>
<th>Year</th>
<th>Age of Housing Units, x (years)</th>
<th>Number of Housing Units Surviving to Age x (in thousands)</th>
<th>Data Points Used to Establish Gompertz Curve</th>
<th>Proportion of Housing Units Lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>0</td>
<td>9882</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>11</td>
<td>12023</td>
<td>1 (t = 12023)</td>
<td>0.000</td>
</tr>
<tr>
<td>1987</td>
<td>13</td>
<td>12003</td>
<td>2 (p = 0.00166)</td>
<td>0.000</td>
</tr>
<tr>
<td>1989</td>
<td>15</td>
<td>11907</td>
<td>3 (R = 0.979)</td>
<td>0.002</td>
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<tr>
<td>1991</td>
<td>17</td>
<td>11452</td>
<td></td>
<td>0.010</td>
</tr>
<tr>
<td>1993</td>
<td>19</td>
<td>11559</td>
<td></td>
<td>0.047</td>
</tr>
<tr>
<td>1995</td>
<td>21</td>
<td>11403</td>
<td></td>
<td>0.047</td>
</tr>
<tr>
<td>1997</td>
<td>23</td>
<td>11592</td>
<td></td>
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</tr>
<tr>
<td>1999</td>
<td>25</td>
<td>11423</td>
<td></td>
<td>0.060</td>
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<tr>
<td>2001</td>
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<td>2005</td>
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<tr>
<td>2007</td>
<td>33</td>
<td>10969</td>
<td></td>
<td>0.139</td>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Age of Housing Units, $x$ (years)</th>
<th>Number of Housing Units Surviving to Age $x$ (in thousands)</th>
<th>Data Points Used to Establish Gompertz Curve</th>
<th>Proportion of Housing Units Lost</th>
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<tr>
<td>1979</td>
<td>0</td>
<td>8264</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>6</td>
<td>14454</td>
<td>$1$ (t = 14454)</td>
<td>0.000</td>
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<tr>
<td>1987</td>
<td>8</td>
<td>12822</td>
<td>$2$ (p = 0.113)</td>
<td>0.113</td>
</tr>
<tr>
<td>1989</td>
<td>10</td>
<td>12829</td>
<td></td>
<td>0.113</td>
</tr>
<tr>
<td>1991</td>
<td>12</td>
<td>12146</td>
<td>$3$ (R = 0.986)</td>
<td>0.160</td>
</tr>
<tr>
<td>1993</td>
<td>14</td>
<td>11915</td>
<td></td>
<td>0.176</td>
</tr>
<tr>
<td>1995</td>
<td>16</td>
<td>12314</td>
<td></td>
<td>0.176</td>
</tr>
<tr>
<td>1997</td>
<td>18</td>
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<td>0.218</td>
</tr>
<tr>
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<td>20</td>
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<td></td>
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<tr>
<td>2001</td>
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<td>12009</td>
<td></td>
<td>0.218</td>
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<tr>
<td>2003</td>
<td>24</td>
<td>12314</td>
<td></td>
<td>0.218</td>
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<tr>
<td>2005</td>
<td>26</td>
<td>14350</td>
<td></td>
<td>0.218</td>
</tr>
<tr>
<td>2007</td>
<td>28</td>
<td>14404</td>
<td></td>
<td>0.218</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Age of Housing Units, x (years)</th>
<th>Number of Housing Units Surviving to Age x (in thousands)</th>
<th>Data Points Used to Establish Gompertz Curve</th>
<th>Proportion of Housing Units Lost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>1</td>
<td>8480</td>
<td>( (t = 8480) )</td>
<td>0.000</td>
</tr>
<tr>
<td>1987</td>
<td>3</td>
<td>8306</td>
<td>( (p = 0.0205) )</td>
<td>0.021</td>
</tr>
<tr>
<td>1989</td>
<td>5</td>
<td>8182</td>
<td>( (R = 0.971) )</td>
<td>0.035</td>
</tr>
<tr>
<td>1991</td>
<td>7</td>
<td>8292</td>
<td></td>
<td>0.035</td>
</tr>
<tr>
<td>1993</td>
<td>9</td>
<td>8143</td>
<td></td>
<td>0.053</td>
</tr>
<tr>
<td>1995</td>
<td>11</td>
<td>8257</td>
<td></td>
<td>0.053</td>
</tr>
<tr>
<td>1997</td>
<td>13</td>
<td>7735</td>
<td></td>
<td>0.114</td>
</tr>
<tr>
<td>1999</td>
<td>15</td>
<td>7684</td>
<td></td>
<td>0.120</td>
</tr>
<tr>
<td>2001</td>
<td>17</td>
<td>7664</td>
<td></td>
<td>0.123</td>
</tr>
<tr>
<td>2003</td>
<td>19</td>
<td>7584</td>
<td></td>
<td>0.132</td>
</tr>
<tr>
<td>2005</td>
<td>21</td>
<td>7517</td>
<td></td>
<td>0.140</td>
</tr>
<tr>
<td>2007</td>
<td>23</td>
<td>7474</td>
<td></td>
<td>0.145</td>
</tr>
</tbody>
</table>

Table 2.4. The Weibull model constants used to create the housing unit service life distributions.

<table>
<thead>
<tr>
<th>Housing Cohort</th>
<th>Weibull model constants</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>( \alpha )</td>
</tr>
<tr>
<td>1970-74</td>
<td>2.4786</td>
</tr>
<tr>
<td>1975-79</td>
<td>0.7937</td>
</tr>
<tr>
<td>1980-84</td>
<td>1.0719</td>
</tr>
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</table>

The Gompertz and Weibull models predict similar trends in housing decrease over time (Figures 2.1-2.6). The models predicted similar curve shapes for the 1970-74 and 1980-84 housing cohorts. Specifically in the cumulative loss curves (Figures 2.1 and 2.5), the models predict an s-shape curve in that the initial rate of loss is low, the rate of loss increases but stays relatively constant across the middle of the service life distribution, and finally the rate of loss dramatically decreases as the cumulative proportion of housing lost approaches one. The models show a slightly different shape for the 1975-79 cohort (Figure 2.3). The initial rate of loss for the
1975-79 cohort is high but then slowly and continually decreases across the middle of the service life distribution; finally, the rate of loss dramatically decreases as the cumulative proportion of housing lost approaches one.


Table 2.5 lists the average service lives predicted by each model for each cohort of housing. The Gompertz model predicted the average service life of a housing unit to be 68 years for the 1980-84 cohort and 115 years for both the 1970-74 and 1975-79 cohorts. The Weibull model predicted the average service life to be 62 years for the 1970-74 cohort, 153 years for the 1975-79 cohort, and 116 years for the 1980-84 cohort. If the estimates for the three cohorts are averaged, the Gompertz model predicts an average service life of 99 years and the Weibull model predicts an average service life of 110 years for housing constructed in the U.S. between 1970-90. Both models predict average service lives similar to those published in the literature as Skog (2008) estimated the average service life of U.S. housing built between 1960-1999 to be 82-84 years. Winistorfer (2005) estimated the average service life of U.S. housing to be in excess of 85 years. Johnstone (2001a) estimated the average service life of New Zealand housing to be between 90-130 years. Gleeson (1985) estimated the average service life of a
sample of housing in Indianapolis to be 100 years and Johnstone (2001b) used Gleeson’s (1985) data and estimated the average service life of the same sample of Indianapolis housing to be 96-118 years.

Table 2.5. Average service life for housing constructed in the United States estimated by a Gompertz model and a two-parameter Weibull model.

<table>
<thead>
<tr>
<th>Time period of housing construction</th>
<th>Average service life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gompertz Model</td>
</tr>
<tr>
<td>1970-74</td>
<td>115</td>
</tr>
<tr>
<td>1975-79</td>
<td>115</td>
</tr>
<tr>
<td>1980-84</td>
<td>68</td>
</tr>
<tr>
<td>Average across the three time periods</td>
<td>99</td>
</tr>
</tbody>
</table>

The Gompertz and Weibull models predict similar service lives as the other estimates previously listed. Unfortunately there are no current means to validate either of the models as the actual data is limited. Reaching back in time for data was limited to 1970 in an effort to avoid skewing the curve fits due to differences in construction techniques and materials. Additional data would undoubtedly provide more accurate curve fits with the Weibull models. Thus, these curve fits and the subsequent estimations should be revised as additional data becomes available in the future.

Conclusion

The average service life of residential structures was predicted to be between 62 and 153 years. If the three Weibull estimates are averaged, the predicted service life of residential structures is 110 years. The service life distributions can be used to estimate the future demand for residential building products. Additionally, the service life distributions can be used to gain
some insight into the mechanical exposure of residential building materials through estimation of the time in service in combination with the expected loadings.

In this work, the service life of inaccessible building components was assumed to be the same as the structure they are a part of, future research should evaluate if this assumption is valid. Additionally, the service life of reused materials should be examined to determine if subsequent uses span the same duration as the initial use.

References


CHAPTER THREE

Experimental Characterization of the Effects of Diameter and Wall Thickness on Hollow Fastener Behavior

Abstract

Reuse and recycling represent opportunities to reduce virgin raw material demands associated with construction activities. It is apparent that the application of design for deconstruction concepts combined with a fastening methodology that enables deconstruction and reduces design event and deconstruction damage is required. The use of hollow fasteners presents an opportunity to overcome some reuse barriers by filling the need for removable fasteners that may reduce bearing substrate material damage. The objective of this research was to develop an understanding of the behavioral characteristics of joints connected with hollow fasteners.

Hollow fasteners were subjected to various shear loadings in test fixtures as well as in lap-joints in order to determine fastener and joint behavior. Constrained shear yield loads were found to be nearly the same as yield loads in test joints where buckling of hollow fasteners was the dominant factor in joint yielding. Yield loads obtained from constrained shear testing of hollow fasteners can be used to predict joint yield loads in lap-joints when joint yielding is primarily due to buckling in the walls of hollow fasteners.

In joints connected with a given hollow fastener diameter, there was no reduction in yield load as wall thickness was decreased until fastener buckling became the dominant factor in joint
yielding. In joints fastened with very thin walled hollow fasteners, joint yielding was primarily
due to buckling of the fastener. It was evident that damage in bearing materials can be reduced
by using thin walled fasteners that buckle before severe deformation occurs in the connected
materials.

Introduction

While some structures are lost due to damage from catastrophic events, not all structures
are demolished due to loss of structural integrity. Johnstone (2001) states that few dwellings are
demolished due to a failure of the structural system and that the potential service life of most
residential structures is not realized. Johnstone (2001) and Bender (1979) attribute residential
structure loss to economic decisions where alternate use of the structure or land on which the
structure is situated favor demolition over continued use of the structure.

Buildings removed from the inventory for reasons other than structural failure contain
materials that have not reached their potential service lives. Certainly a portion of these building
materials would retain sufficient residual strength and service life to provide satisfactory service
in other structures. Falk and McKeever (2004) and Chini (2007) have stated that significant
portions of the demolition waste stream contain reusable materials.

Reuse and recycling represent opportunities to reduce virgin raw material demands
associated with construction activities (Falk and McKeever, 2004). While reuse and recycling
represent opportunities to reduce environmental impacts as well as material and energy
consumption, only limited amounts of reuse and recycling of used building materials has
developed (Webster & Napier, 2003; Leigh & Patterson, 2006). Some of the problems inhibiting
reuse and recycling of building materials are structure design and construction methods. Current
construction methods employ permanent fixing methods and are not designed to be deconstructed (Crowther, 2001; Guy & Shell, 2002).

Removable fasteners that maintain or improve structure ductility while minimizing material damage resulting from deconstruction and catastrophic design events could help facilitate module reuse. The use of hollow fasteners that can absorb energy through deformation in the fastener walls may provide a means to reduce material damage and maintain structure ductility. Through proper selection of hollow fastener diameter, wall thickness, and material, it may be possible to design a joint in which hollow rivets collapse before the critical stresses are reached across a large portion of the bearing substrates. If joint failure is preferentially directed into the fastener, substrate damage due to a design event or deconstruction activities may be reduced leaving the building materials reusable by simply replacing failed fasteners.

Alleviating brittle failure in timber joints through the use of hollow fasteners can be viewed as a similar problem to minimizing damage in bearing substrates. Brittle failure in timber joints often results from rapid crack growth parallel to the grain (Guan and Rodd, 2001). Reducing rapid crack growth and brittle failure in timber members can be accomplished by minimizing damage and stress concentrations incurred in the bearing substrates. Several researchers have investigated the use of hollow rivets, also referred to as tube fasteners, hollow fasteners, or hollow dowels, as a means to improve ductility and prevent brittle failure in timber joints (Cruz and Ceccotti, 1996; Werner, 1996; Leijten, 1999, 2001; Leijten et al, 2004, 2006; Guan and Rodd, 1997, 2000, 2001a, 2001b; Murty, 2005; Murty et al, 2007, 2008). Leijten (1999), as well as Guan and Rodd (2001a, 2001b), combined localized reinforcement through the application of densified veneer wood at the meeting edges of joints with the use of expanded hollow fasteners to reduce brittle joint failure. They both reported reduced brittle failure and
increased energy absorption, which was attributed to the ductile embedment behavior of the DVM as well as to the plastic deformation capacity of the hollow fasteners.

There has been little research aimed at facilitating material reuse and structure repair by employing hollow fasteners to reduce bearing substrate damage. There is a clear need to develop an understanding of the behavioral characteristics of joints fastened with hollow rivets.

The goal of this work is to delineate the mechanical relationships and yield behavior in monotonically loaded lap joints connected with hollow fasteners. The specific objectives within this work include:

1. Delineate the role of fastener diameter and wall thickness in the yield behavior of hollow fasteners under diametric loading, unconstrained shear loading and constrained shear loading.

2. Delineate the role of fastener diameter and wall thickness in the mechanical behavior of LSL lap-joints.

3. Determine the reloading capacities of deconstructed lap-joints.

**Materials and Methods**

**Fasteners**

Hollow fasteners were produced from commercially obtained extruded and seamless, aluminum tubes (6061-T6 alloy tubes produced by Precision Tube Co.). Solid fasteners were extracted from grade 5, hardened steel bolts. Individual test specimens were cut from smooth shafts using a band saw. The ends and edges of all the dowels were de-burred and filed flat. The diameter and wall thickness configurations tested as well and the number of samples for each test are listed in Table 3.1.
Table 3.1. Hollow fastener specimen requirements for each test by diameter and wall thickness.

<table>
<thead>
<tr>
<th>Hollow Fastener Specifications</th>
<th>Number of Hollow Fastener Test Specimens by Test</th>
<th>Number of Lap Joint Test Specimens (single loading)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Diameter (in.)</td>
<td>Nominal Wall Thickness (in.)</td>
<td>Parallel to Load LSL Orientation</td>
</tr>
<tr>
<td>0.25</td>
<td>0.035</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>10</td>
</tr>
<tr>
<td>0.50</td>
<td>0.028</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.035</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.058</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>10</td>
</tr>
<tr>
<td>0.75</td>
<td>0.035</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.083</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>10</td>
</tr>
</tbody>
</table>

Laminated Strand Lumber

All of the wood strand composite test specimens used in the joint tests were extracted from commercially produced laminated strand lumber boards (LSL). The LSL used in this testing was 1.25 inch thick by 14 inch wide, 1.3E rated TimberStrand® Rimboard manufactured in Canada by Weyerhaeuser corporation. LSL was selected because all the flakes are unidirectionally aligned thus eliminating changes in material properties across the LSL thickness that result from cross-oriented flakes. Additionally, the product is produced with a flat vertical density profile (Figure 3.1) reducing variation in mechanical properties across the vertical cross-section while still maintaining many characteristics of common strand-based composites. Prior to testing, the LSL was conditioned at 64°F and 64% relative humidity until equilibration. After equilibration the LSL used in joint testing was planed to nominal thickness of 1 inch, with equal amounts of material removed from each side.
LSL Vertical Density Profile and Moisture Content

Ten, two inch by two inch specimens were randomly selected from the LSL boards for vertical density profile measurements using a QMS Density Profiler Model QDP-01X manufactured by Quintek Measurement Systems, Inc. The vertical density profile averaged across all the density scans is shown in Figure 3.1.

Moisture content samples were extracted from every LSL specimen used in testing. The average moisture content of the specimens was measured to be 9.2% at the time of testing. The moisture content was measured in accordance with ASTM 4442-07, method B.
Diametric and Shear Loading of Hollow Fasteners

All mechanical tests performed on hollow fasteners employed a screw driven universal test machine rated for a maximum load of 30 kips. Digital data acquisition equipment was used to record data from a 30 kip load cell and an internal encoder.

The hollow fasteners were compressed with diametric load imposed with steel plates. One plate was stationary and mounted on the bottom of the test frame while the other self-aligning, flat plate was mounted on the moveable crosshead. The crosshead speed used to test the 0.75 inch diameter and 0.5 inch diameter hollow fasteners was 0.04 inches per minute while the crosshead speed used to test the 0.25 inch diameter hollow fasteners was 0.02 inches per minute. The diameter and wall thickness combinations as well as the number of specimens tested are listed in Table 3.1.

Constrained Shear

Shear loads were applied to hollow fasteners through 1 inch thick by 4 inch wide by 3 inch high steel plates that were aligned to replicate a lap-joint. Hollow fasteners were inserted in holes drilled through the steel plates to replicate a fastened joint. The center of the holes were placed in the middle of the width of the plate and were located one inch from the bottom of the plate. The holes drilled through the steel plates were 1/32 inch greater in diameter than the hollow fasteners they were intended to accept: 9/32 inch holes were drilled through plates used to shear load 0.25 inch diameter fasteners, 17/32 inch holes were drilled through plates used to shear load 0.5 inch diameter fasteners, and 25/32 inch holes were drilled through plates used to shear load 0.75 inch diameter fasteners. One of the steel plates was affixed to the base plate that was mounted on the stationary bottom of the test frame while the other plate was mounted to the
moveable crosshead. A solid, 1 inch thick plate was also affixed to the stationary base plate. The solid plate was used to restrict out of plane movement of the plate affixed to the moveable crosshead. The test apparatus is shown in Figure 3.2.

The crosshead speed used to test the 0.75 inch diameter and 0.5 inch diameter hollow fasteners was 0.04 inches per minute while the crosshead speed used to test the 0.25 inch diameter hollow fasteners was 0.02 inches per minute. The diameter and wall thickness combinations as well as the number of specimens tested are listed in Table 3.1.

**Unconstrained Shear**

Shear loads were applied to hollow fasteners through 1 inch thick by 4 inch wide by 3 inch high steel plates that were aligned to replicate a lap joint. Hollow fasteners were inserted in holes drilled through the steel plates. The centers of the holes were placed in the middle of the width of the plate and were located one inch from the bottom of the plate. To eliminate side constraint effects on yield loads, slots perpendicular to the direction of load and centered on the holes were cut into the plates. To prevent the fasteners from moving out of plane in the slots during testing, the slots were machined with a circular cutter that was smaller than the diameter of the holes drilled through the plates. In the plates used to test 0.25 inch diameter hollow fasteners, 0.28125 inch holes were drilled and 0.4 inch long by 0.25 inch diameter slots were cut through the plates. In the plates used to test 0.5 inch diameter hollow fasteners, 0.53125 inch holes were drilled and 0.8 inch long by 0.46875 inch diameter slots were cut through the plates. In the plates used to test 0.75 inch diameter hollow fasteners, 0.78125 inch holes were drilled and 1.2 inch long by 0.6875 inch diameter slots were cut through the plates.
One of the steel plates was affixed to the base plate that was mounted on the stationary bottom of the test frame while the other plate was mounted to the moveable crosshead. A solid, 1 inch thick plate was also affixed to the stationary base plate. The solid plate was used to restrict out of plane movement of the plate affixed to the moveable crosshead. The test apparatus is shown in Figure 3.2. The crosshead speed used to test the 0.75 inch diameter and 0.5 inch diameter hollow fasteners was 0.04 inches per minute while the crosshead speed used to test the 0.25 inch diameter hollow fasteners was 0.02 inches per minute. The diameter and wall thickness combinations as well as the number of specimens tested are listed in Table 3.1.

**Figure 3.2.** Unconstrained shear fixture.

**Joint Testing, Single Loading**

Monotonic connection tests were conducted according to ASTM D5652-95. Individual test specimens consisted of two pieces of TimberStrand LSL whose nominal dimensions were 6 inches wide by 6 inches long by 1 inch thick and 6 inches wide by 14 inches long by 1 inch thick. In each joint test specimen, LSL components were connected by a single hollow fastener inserted through predrilled holes in each piece of LSL. The holes drilled through the LSL
components were 1/32 inches greater in diameter than the connectors used to fasten the components. The center of the holes drilled through the 6”x6” LSL pieces were located 3 inches from the edges of the pieces. The center of the holes drilled through the 6”x14” LSL pieces were located 3 inches from the sides of the pieces and 6 inches from the top edge of the pieces. The hollow fasteners used to connect the LSL components were 2.25 inches long and did not feature end fixity.

Prior to the holes being bored for the fasteners, each LSL component within the sample set was weighed and measured. After the holes were bored through the LSL pieces, each piece in the sample set was reweighed. The apparent density of the removed material from each component was determined and LSL components were sorted and matched by density as closely as possible. After drilling, reweighing, and pairing for joint specimens, LSL components were returned to the conditioning chamber until they were used in joint testing.

The diameter and wall thickness combinations as well as the number of specimens tested are listed in Table 3.1. The testing apparatus is shown in Figure 3.3. The 6”x6” LSL portion of the joint was stationary and rested on a flat platform on the test fixture. The 6”x14” LSL portion of the joint was the moveable side and was supported by roller bearings along the side opposite the 6”x6” LSL piece as well as by a roller bearing directly below the 6”x6” piece. The roller bearings prevented the 6”x14” LSL component from rotating out of plane. The load was applied to the 6”x14” LSL joint component via a plate mounted to the moveable crosshead. The crosshead speed used to test joints connected with 0.75 and 0.5 inch diameter fasteners was 0.04 inches per minute while the crosshead speed used to test joints connected with 0.25 inch diameter fasteners was 0.02 inches per minute. Joint displacement was measured at the center of the joint using a one-inch stroke linear variable differential transducer (LVDT). Joint yield was
determined through finding the intersection of a line projected along the linear elastic range of the load-displacement test data curve and a line projected along the load-displacement test data curve after yield had occurred. The intersection of the lines marked the point of yield.

**Joint Testing, Multiple Loadings**

Twelve joints with the LSL oriented parallel to the direction of load (parallel joints) and an additional twelve joints with the LSL oriented perpendicular to the direction of load (perpendicular joints) were connected with hollow fasteners and subjected to multiple loadings. The joint configuration and testing apparatus were as previously described. The initial loading was performed on joints connected with hollow fasteners that were 0.5 inches in diameter and had walls that were 0.028 inches thick. For the initial load application, the joint was loaded at a crosshead speed of 0.04 inches per minute until joint displacement reached 0.25 inches. After the initial loading, Run 1, the original fastener was removed and replaced with a new 0.5 inch diameter hollow fastener that had 0.028 inch thick walls. After a waiting period of at least 6.5 minutes, the fastener was replaced and the joint was reloaded at a crosshead speed of 0.04 inches per minute until joint displacement of 0.6 inches was achieved. After the second loading, Run 2, the joints were disassembled and allowed to rest overnight. Prior to the third loading, Run 3, the original holes were drilled out to 25/32 inches in diameter. The joint was reassembled and connected with a 0.75 inch diameter fastener that had 0.035 inch thick walls. The third loading of the LSL substrates was performed at a crosshead speed of 0.04 inches per minute and was continued until the joint was displaced 0.35 inches. Following the third loading, the 0.75 inch diameter fastener was removed and replaced with a new 0.75 inch diameter hollow fastener that had 0.035 inch thick walls. After a waiting period of at least 8 minutes and 45 seconds the joint
was reassembled with a new fastener and reloaded at a crosshead speed of 0.04 inches per
minute until joint displacement of 0.75 inches was achieved, Run 4. Joint yield loads were
determined from each loading as described previously. Joint slack between the first and second
loadings was defined as the distance the crosshead moved before the joint began to resist loading
relative to the initial loading.

Twelve parallel joints and twelve perpendicular joints were also connected with solid
fasteners and subjected to multiple loadings. The joint configuration and testing apparatus were
as previously described. The solid dowels did not feature end fixity. Runs 1 through 3 were as
described above. Run 4 was omitted for joint tests using solid dowels.

Figure 3.3. Joint testing apparatus.
Results and Discussion

Hollow Fastener Characterization

In all three hollow fastener testing configurations, yield loads increased with increasing diameter and increasing wall thickness (Table 3.2). In diametric loading, hollow fastener yield was marked by flattening of the fastener directly below the applied load. Similarly, hollow fastener yield in the unconstrained shear test configuration was marked initially by a decrease in diameter below the applied load. Upon continued loading, the fasteners were sheared apart by the test fixture. Fastener flattening below the applied load marked hollow fastener yield in the constrained test configuration. In the constrained test fixture, brittle failure of the fastener occurred shortly after yield.

Table 3.2. Yield loads in hollow fasteners from different loading configurations.

<table>
<thead>
<tr>
<th>Nominal Outside Diameter (in.)</th>
<th>Nominal Wall Thickness (in.)</th>
<th>Ri/Ro</th>
<th>Constrained Shear Test, Yield Load (lb) (%COV)</th>
<th>Unconstrained Shear Test, Yield Load (lb) (%COV)</th>
<th>Diametric Loading, Yield Load (lb/linear in.) (%COV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.035</td>
<td>0.72</td>
<td>508 (2.96)</td>
<td>461 (0.89)</td>
<td>573 (1.20)</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>0.61</td>
<td>833 (1.40)</td>
<td>655 (1.52)</td>
<td>1286 (1.54)</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>0.48</td>
<td>969 (1.60)</td>
<td>909 (2.39)</td>
<td>2252 (2.23)</td>
</tr>
<tr>
<td>0.50</td>
<td>0.028</td>
<td>0.89</td>
<td>696 (2.80)</td>
<td>285 (2.31)</td>
<td>130 (0.80)</td>
</tr>
<tr>
<td></td>
<td>0.035</td>
<td>0.86</td>
<td>933 (2.28)</td>
<td>372 (1.54)</td>
<td>211 (1.34)</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>0.80</td>
<td>1406 (2.29)</td>
<td>672 (1.90)</td>
<td>494 (4.11)</td>
</tr>
<tr>
<td></td>
<td>0.058</td>
<td>0.77</td>
<td>1611 (1.61)</td>
<td>870 (1.03)</td>
<td>644 (1.03)</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>0.74</td>
<td>1897 (6.15)</td>
<td>1237 (1.82)</td>
<td>944 (1.63)</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0.50</td>
<td>3190 (2.56)</td>
<td>2854 (1.14)</td>
<td>3715 (1.23)</td>
</tr>
<tr>
<td>0.75</td>
<td>0.035</td>
<td>0.91</td>
<td>1227 (4.06)</td>
<td>411 (3.37)</td>
<td>136 (0.59)</td>
</tr>
<tr>
<td></td>
<td>0.083</td>
<td>0.78</td>
<td>3754 (2.79)</td>
<td>2210 (1.88)</td>
<td>1063 (1.29)</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0.67</td>
<td>4699 (2.35)</td>
<td>3470 (2.24)</td>
<td>2393 (0.99)</td>
</tr>
</tbody>
</table>

For each diameter and wall thickness combination tested, constrained shear yield loads were higher than unconstrained yield loads. Clearly constraint along the outside edge of the
hollow fastener prevented fastener buckling via diameter increase, resulting in the higher yield loads.

For 0.5 and 0.75 inch diameter hollow fasteners with wall thicknesses greater than 0.065 inches, fastener yield loads were greatest in the constrained test configuration followed by the unconstrained and diametric loading configurations (Figures 3.5 and 3.6). This trend is not seen in the test results for the 0.25 inch diameter hollow fasteners (Figure 3.4). The different behavior with the 0.25 inch hollow fasteners is due to the relative difference in constraint compared to that with the other diameters. The holes in the shear test fixtures were made 1/32 inches greater in diameter regardless of the diameter of the fastener being tested. Therefore, the relative level of constraint would be less for 0.25 inch diameter fasteners than it would be for 0.5 inch and 0.75 inch diameter fasteners.

![Graph](image)

**Figure 3.4.** Yield loads by wall thickness for 0.25 inch diameter hollow fasteners across different loading configurations.
Figure 3.5. Yield loads by wall thickness for 0.50 inch diameter hollow fasteners across different loading configurations.

Figure 3.6. Yield loads by wall thickness for 0.75 inch diameter hollow fasteners across different loading configurations.
While the diametric loading condition is not directly equivalent to either of the shear configurations, it is included and compared with the two shear configurations to determine if plane stress and strain conditions can be assumed. Future efforts to using mechanics of materials based modeling would be made much easier if plane stress or strain could be assumed. The diametric loading yield results are reported in pounds per linear inch. As the hollow fastener shear specimens were two inches long, with each side of the shear fixture containing one inch of the hollow fastener shear specimen, the yield loads obtained through diametric loading would be comparable to the yield loads found in unconstrained shear testing if plane stress and strain assumptions were valid and if fastener yield was due to wall buckling. Under plane stress conditions with the hollow fastener specimen sizes used in this work, thin walled diametrically loaded hollow fasteners should yield at loads similar to those found in the unconstrained shear test configurations. For 0.5 inch and 0.75 inch diameter hollow fasteners with wall thicknesses less than 0.065 inches, the unconstrained shear yield loads were greater than the yield load per linear inch found in diametrically loaded hollow fasteners. The differences in these yield loads are likely due to multi-axial stresses, specifically, out of plane stresses along the length of the fastener in the unconstrained shear test configurations. In the unconstrained test configuration both bending stresses and tensile stresses can develop along the length of the test specimen between the two shear plates. These stresses cannot develop in diametric loading as the entire length of the test specimen is subjected to the same load conditions. The data indicates that for the wall thickness tested, plane stress and strain assumptions are not valid.
Single Load Application Lap Joint Testing

In parallel or perpendicular joints fastened with 0.5 inch diameter dowels, yield loads did not decrease with decreasing wall thickness until the mode of yield was dominated by buckling of the walls in the hollow fasteners (Table 3.3). The change in the mode of yield was evident visually as fastener distortion increased (Figure 3.7) while deformation in the LSL decreased. Additionally, the shift in yield mode was accompanied with a marked drop in the coefficients of variance (COV) in the yield load. The decrease in the yield load COV’s was due to energy absorption being concentrated in the fasteners though deformation which resulted in more consistent yield loads due to the much higher degree of homogeneity in metals compared to that of the LSL. Also, for joints in which buckling in the walls of the hollow fastener was the dominant mode of yield, the slope of the load-displacement curve became mostly flat after yield (Figures 3.8 and 3.9). In both parallel and perpendicular joints, joint yielding was dominated by buckling in the walls of the hollow fastener in 0.5 inch diameter fasteners with 0.035 inch and 0.028 inch thick walls.
Wall thickness = 0.028 in.

Wall thickness = 0.035 in.

Wall thickness = 0.049 in.

Wall thickness = 0.058 in.

Wall thickness = 0.065 in.

Wall thickness = 0.125 in.

Solid fastener

**Figure 3.7.** Deformation in 0.5 inch diameter fasteners of various wall thicknesses at a joint displacement of 0.6 inches.
### Table 3.3. Yield load in lap joints fastened with hollow and solid fasteners.

<table>
<thead>
<tr>
<th>Nominal Fastener Diameter (in.)</th>
<th>Nominal Wall Thickness for Hollow Dowels</th>
<th>Ri/Ro</th>
<th>Yield Loads for Parallel Joints (lb)</th>
<th>Yield Loads for Perpendicular Joints (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(%COV)</td>
<td>(%COV)</td>
</tr>
<tr>
<td>0.25</td>
<td>0.035</td>
<td>0.72</td>
<td>437 (16.0)</td>
<td>399 (14.4)</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0</td>
<td>382 (24.8)</td>
<td>331 (18.1)</td>
</tr>
<tr>
<td>0.50</td>
<td>0.028</td>
<td>0.89</td>
<td>686 (6.4)</td>
<td>707 (2.7)</td>
</tr>
<tr>
<td></td>
<td>0.035</td>
<td>0.86</td>
<td>893 (5.20)</td>
<td>891 (3.50)</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>0.80</td>
<td>1150 (21.10)</td>
<td>893 (13.90)</td>
</tr>
<tr>
<td></td>
<td>0.058</td>
<td>0.77</td>
<td>1035 (16.50)</td>
<td>842 (24.70)</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>0.74</td>
<td>1025 (14.80)</td>
<td>837 (15.9)</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0.50</td>
<td>1139 (20.00)</td>
<td>793 (16.60)</td>
</tr>
<tr>
<td></td>
<td>0.250</td>
<td>0</td>
<td>1006 (12.1)</td>
<td>734 (24.6)</td>
</tr>
<tr>
<td>0.75</td>
<td>0.035</td>
<td>0.91</td>
<td>1240 (4.0)</td>
<td>1290 (7.3)</td>
</tr>
<tr>
<td></td>
<td>0.375</td>
<td>0</td>
<td>1304 (12.0)</td>
<td>1065 (16.3)</td>
</tr>
</tbody>
</table>
Figure 3.8. Typical load displacement curves from the loading of parallel lap-joints connected with 0.50 inch diameter fasteners.

Figure 3.9. Typical load displacement curves from the loading of perpendicular lap-joints connected with 0.50 inch diameter fasteners.
Parallel and perpendicular joints fastened with 0.5 inch diameter fasteners with wall thicknesses of 0.035 or less yielded primarily due to fastener buckling. Yield load decreased with decreasing wall thickness when joint yield was primarily due to fastener buckling (Figures 3.7, 3.10 and 3.11). Joint yield loads did not decrease with a decrease in fastener wall thickness when fastener buckling was not the primary cause of joint yield (Figures 3.7, 3.10, and 3.11).

**Figure 3.10.** Wall thickness vs. yield load in parallel joints fastened with 0.5 inch diameter dowels.
Figure 3.11. Wall thickness vs. yield load in perpendicular joints fastened with 0.5 inch diameter dowels.

Additional joints of both LSL orientations, which were fastened with solid 0.25 inch and 0.75 inch diameter dowels as well as hollow dowels that were 0.25 inches in diameter with 0.035 inch thick walls and 0.75 inch diameter dowels with 0.035 inch walls, were tested. The 0.035 inch wall thicknesses were chosen for both 0.25 inch and 0.75 inch diameters as they were the thinnest walls available for those diameters in aluminum 6061-T6 seamless tubes at the time of testing. Load displacement curves for joints fastened with 0.25 inch and 0.75 inch diameter dowels are shown in Figures 3.12 and 3.13. Yield in the joints fastened with 0.75 inch diameter fasteners with the 0.035 inch walls was dominated by buckling in the walls of the hollow fastener in the parallel joints while yield in the perpendicular joints was due to a combination of wood deformation and fastener buckling. Yield in the joints fastened with the 0.25 diameter fasteners with 0.035 inch thick walls was primarily due to wood deformation with some minor fastener deformation.
Figure 3.12. Typical load displacement curves from parallel lap-joints fastened with 0.25 and 0.75 inch diameter connectors.

Figure 3.13. Typical load displacement curves from perpendicular lap-joints fastened with 0.25 and 0.75 inch diameter connectors.
When comparing the hollow fastener test results to the yield values found in joint testing (Tables 3.2 and 3.4), it is apparent that the unconstrained shear and the diametrically loaded fastener test configurations do not represent the conditions found in loaded joints of the configuration used in this testing. However, the yield load values obtained in the constrained shear testing of the hollow fasteners were very similar to the yield values seen in test joints where yield was dominated by wall buckling in the hollow fasteners (Table 3.4). While the level of constraint provided by the steel test fixture is greater than that provided by the LSL, the data indicates that yield loads found in the constrained shear testing may provide good estimates of joint yield when fastener buckling dominates joint yielding.

**Table 3.4.** Comparison of yield loads found in constrained shear testing of select hollow dowels and yield loads found in the testing of joints fastened with select hollow dowels.

<table>
<thead>
<tr>
<th>Hollow Fastener Description (diameter x wall thickness) (in.)</th>
<th>Constrained Shear Testing, Yield Load (lbs) (COV%)</th>
<th>Joint Test, LSL Oriented Parallel to the Applied Load, Yield Load (lbs) (COV%)</th>
<th>Joint Test, LSL Oriented Perpendicular to the Applied Load, Yield Load (lbs) (COV%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50 x 0.028</td>
<td>696 (2.80)</td>
<td>686 (6.4)</td>
<td>707 (2.7)</td>
</tr>
<tr>
<td>0.50 x 0.035</td>
<td>933 (2.28)</td>
<td>893 (5.20)</td>
<td>891 (3.50)</td>
</tr>
<tr>
<td>0.75 x 0.035</td>
<td>1227 (4.06)</td>
<td>1240 (4.0)</td>
<td>1290 (7.3)</td>
</tr>
</tbody>
</table>

**Multiple Joint Loadings of LSL Components - Parallel LSL Orientation**

In parallel joints connected with hollow fasteners there were some deleterious effects caused by the initial loading, Run 1, which became apparent in the subsequent loading, Run 2. There was a slight decrease in yield load between Run 1 and Run 2 that was statistically significant, p-value equal to 0.0481 (Tables 3.5 and 3.6). There was an average of 0.023 inches
of joint slack resulting from the initial loading. The slack is due to permanent deformation in the LSL resulting from Run 1 loading. The difference in displacement at yield between Runs 1 and 2 was statistically insignificant. Figure 3.14 shows a shift in displacement between the Runs 1 and 2. The shift in displacement between Runs 1 and 2 was caused by LSL deformation incurred in Run 1. Permanent wood deformation remaining from Run 1 required more joint displacement to occur before the hollow dowel could be brought into contact with the wood and be loaded in Run 2.

Table 3.5. Average yield loads and displacements in parallel lap-joints that were connected with hollow and solid fasteners and in which the LSL components were subjected to multiple loadings. Note, joint slack is not included in the displacements.

<table>
<thead>
<tr>
<th></th>
<th>Fastener Diameter = 0.5 in. Wall Thickness = 0.028 in.</th>
<th>Fastener Diameter = 0.75 in. Wall Thickness = 0.035 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hollow Dowels</strong></td>
<td>Run 1</td>
<td>Run 2</td>
</tr>
<tr>
<td>Yield Load (lb)</td>
<td>686</td>
<td>637</td>
</tr>
<tr>
<td>(%COV)</td>
<td>(6.4)</td>
<td>(8.9)</td>
</tr>
<tr>
<td>Displacement at Yield Load (in.) (%COV)</td>
<td>0.0959</td>
<td>0.1117</td>
</tr>
<tr>
<td>Joint Slack Resulting From 0.25 in. Displacement (in.) (%COV)</td>
<td>0.0230</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>(27.2)</td>
<td></td>
</tr>
<tr>
<td><strong>Solid Dowels</strong></td>
<td>Fastener Diameter = 0.5 in.</td>
<td>Fastener Diameter = 0.75 in.</td>
</tr>
<tr>
<td>Yield Load (lb)</td>
<td>Run 1</td>
<td>Run 2</td>
</tr>
<tr>
<td>(%COV)</td>
<td>927</td>
<td>1509</td>
</tr>
<tr>
<td>Displacement at Yield Load (in.) (%COV)</td>
<td>0.0968</td>
<td>(17.3)</td>
</tr>
<tr>
<td>Joint Slack Resulting From 0.25 in. Displacement (in.) (%COV)</td>
<td>0.1238</td>
<td>(13.8)</td>
</tr>
<tr>
<td></td>
<td>(14.9)</td>
<td>(17.5)</td>
</tr>
</tbody>
</table>
Table 3.6. Statistical test results from average yield loads and displacements from parallel lap-joints that were connected with hollow and solid fasteners and in which the LSL components were subjected to multiple loadings.

<table>
<thead>
<tr>
<th>Dowel Type</th>
<th>Data Set 1</th>
<th>Data Set 2</th>
<th>T-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hollow</td>
<td>Run 1 Yield</td>
<td>Run 2 Yield</td>
<td>2.2228</td>
<td>0.0481</td>
</tr>
<tr>
<td></td>
<td>Run 1 Displacement</td>
<td>Run 2 Displacement</td>
<td>-2.1687</td>
<td>0.0529</td>
</tr>
<tr>
<td></td>
<td>Run 3 Yield</td>
<td>Run 4 Yield</td>
<td>-0.7875</td>
<td>0.4476</td>
</tr>
<tr>
<td></td>
<td>Run 3 Displacement</td>
<td>Run 4 Displacement</td>
<td>-5.4854</td>
<td>0.0002</td>
</tr>
<tr>
<td>Hollow</td>
<td>Run 3 Yield</td>
<td>Baseline Yield</td>
<td>-0.5423</td>
<td>0.5931</td>
</tr>
<tr>
<td></td>
<td>Run 3 Displacement</td>
<td>Baseline Displacement</td>
<td>0.8763</td>
<td>0.3903</td>
</tr>
<tr>
<td></td>
<td>Run 4 Yield</td>
<td>Baseline Yield</td>
<td>0.4527</td>
<td>0.6552</td>
</tr>
<tr>
<td></td>
<td>Run 4 Displacement</td>
<td>Baseline Displacement</td>
<td>5.0028</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Solid</td>
<td>Run 2 Yield</td>
<td>Baseline Yield</td>
<td>2.3438</td>
<td>0.0285</td>
</tr>
<tr>
<td></td>
<td>Run 2 Displacement</td>
<td>Baseline Displacement</td>
<td>-20.2421</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Figure 3.14. Typical load displacement curves from multiple loadings of parallel lap-joints where the fastener was replaced between loadings.
The LSL used to construct joints for Run 3 had been drilled out to remove the material damaged in Runs 1 and 2. Run 3 joints required a larger diameter hollow connector in order to fill the void left from removal of the damaged material. Run 3 joints, constructed with LSL components which were subjected to loadings in Runs 1 and 2, and connected with a 0.75 inch hollow dowel with 0.035 inch thick walls, performed similarly to joints constructed with the same size and type of fastener but with virgin LSL. No statistically significant difference in yield load and displacement at yield were found between Run 3 and the baseline (Tables 3.5 and 3.6).

Reuse of the LSL from Run 3, with the damaged hollow fastener replaced with a new hollow fastener, produced joints that had greater deflection at yield in Run 4. The increase in deflection is due to permanent deformation incurred in Run 3. Unlike Runs 1 and 2, there was no decrease in yield load between Runs 3 and 4.

In test joints subjected to 0.25 inches of joint displacement, more joint slack was created in joints connected with solid fasteners than was created in joints connected with hollow fasteners (Table 3.5). The difference in joint slack was related to the different yield mechanisms seen between the solid and thin walled hollow dowels. The dominant yield mode in joints connected with 0.5 inch diameter dowels with 0.028 inch thick walls was buckling of the dowel. However, the yield mode in the joints fastened with solid dowels was rigid dowel rotation, referred to as Type II yield in the National Design Specification for Wood Construction (AF&PA, 2005) and in The General Dowel Equations for Calculating Lateral Connection Values (AF&PA, 1999). All the energy adsorption in joints connected with the solid dowels was through deformation in the LSL. In Run 2, the joint displacement was increased to 0.6 inches.
The increased displacement did not alter the primary modes of yield in either the joints connected with hollow or solid dowels.

After the joints connected with 0.5-inch diameter, solid dowels were subjected to 0.6 inch displacements, Run 1, the LSL components were drilled out to 25/32 inches, refastened with 0.75 inch diameter, solid dowels and reloaded. Run 2 results were compared to values found from the testing of joints using virgin LSL which were connected with 0.75 inch solid dowels, baseline values. The average yield load found in the refurbished joints connected with 0.75 inch diameter solid dowels was greater than that found with virgin LSL connected with 0.75 inch solid dowels. Additionally the displacement at yield was greater in the refurbished joints than in those using virgin LSL.

In the joints connected with solid dowels, the differences in both yield load and displacement at yield between Runs 1 and 2 resulted from LSL deformation in Run 1. When the LSL materials were reconditioned by expanding the dowel pilot hole to 25/32 inches in diameter, some of the damaged LSL remained as the area impacted by previously loading was greater than the area removed by the 25/32 inch drill bit. The increase in displacement at yield in Run 2 relative to baseline values was due to deformation in the material in the area under the solid dowels that remained after refurbishment. The channel of deformation remaining from Run 1 was smaller in diameter than the replacement dowels used in Run 2. The remaining deformation channels created voids under the larger replacement dowels. The voids under the 0.75 inch diameter dowels left the LSL to resist loads along a reduced area of the solid dowel until sufficient rotation of the dowel was achieved to push through the voids and engage LSL around the entire loading surface of the solid dowel. The rotation required for a complete engagement
of the LSL along the half circumference of the dowel caused an increase in displacement at yield relative to Run 1.

In the joints fastened with solid dowels, permanent deformation in Run 1 likely created densified regions in the LSL that resisted the loading. The increase in yield load between the refurbished joints, Run 2, and those created with virgin materials may have resulted from the densification of some material in Run 1. Gibson and Ashby (1988) have extensively described an increase in strength associated with densification in cellular solids. Additional researchers have established a clear relationship between the strength of strand composites and density (Kelly, 1977; Haygreen and Boyer, 1989; Maloney, 1993; Wang and Winistorfer, 2000; Wang et al, 2007).

**Multiple Joint Loadings of LSL Components - Perpendicular LSL Orientation**

Several of the trends and effects seen between subsequent joint loadings where the LSL was oriented parallel to the direction of load are also evident in joints where the LSL was oriented perpendicular to the applied load. In the perpendicular joints fastened with 0.5 inch diameter hollow dowels, there was a decrease in yield loads between Run 1 and Run 2 (Tables 3.7 and 3.8). While the decrease in yield load is attributed to the same reasons as that for the parallel joints, there was a decrease in the displacement at yield between Run 1 and 2 in the perpendicular joints. Comparisons between Run 3 and Run 4 as well as between Run 4 and the baseline values for perpendicular joints fastened with 0.75 inch diameter hollow dowels with 0.035 inch thick walls, showed the same general changes and trends as seen in the parallel joints. Examination of the perpendicular joints load-displacement graphs shows the same shift in the curves between Run 3 and Run 4 as was seen in the parallel joints.
Table 3.7. Average yield loads and displacements in perpendicular lap-joints that were connected with hollow and solid fasteners and in which the LSL components were subjected to multiple loadings. Note, joint slack is not included in the displacements.

<table>
<thead>
<tr>
<th>Hollow Dowels</th>
<th>Average Test Values</th>
<th>Fastener Diameter = 0.5 in. Wall Thickness = 0.028 in.</th>
<th>Fastener Diameter = 0.75 in. Wall Thickness = 0.035 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 1</td>
<td>Run 2</td>
<td>Run 3</td>
</tr>
<tr>
<td>Yield Load (lb)</td>
<td>707</td>
<td>650</td>
<td>1222</td>
</tr>
<tr>
<td>(%COV)</td>
<td>(2.7)</td>
<td>(9.7)</td>
<td>(9.5)</td>
</tr>
<tr>
<td>Displacement at Yield Load (in.)</td>
<td>0.1266</td>
<td>0.1105</td>
<td>0.1601</td>
</tr>
<tr>
<td>(%COV)</td>
<td>(10.4)</td>
<td>(12.1)</td>
<td>(9.1)</td>
</tr>
<tr>
<td>Joint Slack Resulting From 0.25 in. Displacement (in.)</td>
<td>0.0303</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>(%COV)</td>
<td>(41.3)</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solid Dowels</th>
<th>Average Test Values</th>
<th>Fastener Diameter = 0.5 in.</th>
<th>Fastener Diameter = 0.75 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 1</td>
<td>Run 2</td>
<td>Base Values</td>
</tr>
<tr>
<td>Yield Load (lb)</td>
<td>699</td>
<td>1210</td>
<td>1065</td>
</tr>
<tr>
<td>(%COV)</td>
<td>(20.1)</td>
<td>(17.1)</td>
<td>(16.3)</td>
</tr>
<tr>
<td>Displacement at Yield Load (in.)</td>
<td>0.1319</td>
<td>0.2130</td>
<td>0.1458</td>
</tr>
<tr>
<td>(%COV)</td>
<td>(10.3)</td>
<td>(12.5)</td>
<td>(16.8)</td>
</tr>
<tr>
<td>Joint Slack Resulting From 0.25 in. Displacement (in.)</td>
<td>0.1072</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>(%COV)</td>
<td>(12.1)</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
Table 3.8. Statistical test results from average yield loads and displacements from perpendicular lap-joints that were connected with hollow and solid fasteners and in which the LSL components were subjected to multiple loadings.

<table>
<thead>
<tr>
<th>Dowel Type</th>
<th>Data Set 1</th>
<th>Data Set 2</th>
<th>T-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hollow</td>
<td>Run 1 Yield</td>
<td>Run 2 Yield</td>
<td>10.9643</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Run 1</td>
<td>Run 2</td>
<td>4.4255</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>Run 3 Yield</td>
<td>Run 4 Yield</td>
<td>-1.0553</td>
<td>0.3139</td>
</tr>
<tr>
<td></td>
<td>Run 3 Displacement</td>
<td>Run 4 Displacement</td>
<td>-3.5739</td>
<td>0.0044</td>
</tr>
<tr>
<td>Hollow</td>
<td>Run 3 Yield</td>
<td>Baseline</td>
<td>-0.4817</td>
<td>0.6348</td>
</tr>
<tr>
<td></td>
<td>Run 3 Displacement</td>
<td>Baseline</td>
<td>-0.1556</td>
<td>0.8775</td>
</tr>
<tr>
<td></td>
<td>Run 4 Yield</td>
<td>Baseline</td>
<td>-0.8261</td>
<td>0.4176</td>
</tr>
<tr>
<td></td>
<td>Run 4 Displacement</td>
<td>Baseline</td>
<td>3.8317</td>
<td>0.0009</td>
</tr>
<tr>
<td>Solid</td>
<td>Run 2 Yield</td>
<td>Baseline</td>
<td>1.8652</td>
<td>0.0755</td>
</tr>
<tr>
<td></td>
<td>Run 2 Displacement</td>
<td>Baseline</td>
<td>6.4552</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Figure 3.15. Typical load displacement curves from multiple loadings of perpendicular lap-joints where the fastener was replaced between loadings.
Examination of the results from the perpendicular joints fastened with solid dowels also shows the same general trends as those seen in the parallel joints. In Run 2, joint displacement was increased to 0.6 inches. The increased displacement did not alter the primary modes of yield in either the joints connected with hollow or solid dowels. The perpendicular joint yielding mechanisms were the same as those noted for the parallel joints. Accordingly, the perpendicular joints fastened with solid dowels also showed an increase in yield load and displacement at yield between Run 2 and the baseline values.

**Summary and Conclusions**

For a fixed fastener diameter, increases in wall thickness cause an increase in the diametric, unconstrained, and constrained shear yield loads for fasteners. For a fixed wall thickness, increases in diameter caused an increase in the diametric, unconstrained and constrained shear yield loads for fasteners.

Increases in fastener diameter for a fixed wall thickness caused an increase in joint yield load in both the parallel and perpendicular LSL orientations. When joint yield was primarily due to fastener buckling, yield loads decreased with decreasing wall thickness. When joint yield involved a combination of tube deformation and LSL deformation, yield load did not decrease with decreasing fastener wall thickness.

In loaded joints where yield was primarily due to fastener buckling, reuse of the LSL materials through simple fastener replacement produced joints with slightly lower yield loads and, generally, with higher displacements at yield. Also in joints where yield was primarily due to fastener buckling, removal of damaged material and refastening with a larger hollow
connector produced a joint which performed the same as those constructed with the same size fastener and virgin LSL.

Future research characterizing hollow fastener behavior should include more ductile materials such as polymers. Additionally, more work is needed to determine how damage is accumulated in bearing materials subjected to repeated loadings and which are connected with hollow fasteners. Another knowledge gap that should be addressed is how joints connected with hollow fasteners respond to cyclic loading.

References


CHAPTER FOUR

Modeling the Effects of Diameter and Wall Thickness on Hollow Fastener Behavior

Abstract

Reuse and recycling represent opportunities to reduce virgin raw material demands associated with construction activities. It is apparent that the application of design for deconstruction concepts combined with a fastening methodology that enables deconstruction and reduces design event and deconstruction damage is required. The use of hollow fasteners presents an opportunity to overcome some reuse barriers by filling the need for removable fasteners that may reduce bearing substrate material damage. The specific objectives within this work were to determine joint yielding behavior as related to hollow dowel diameter and wall thickness, and to establish a method to design lap-joints such that yield is initiated primarily through fastener buckling.

Empirical models were applied to test data to describe hollow fastener yield behavior and laminated strand lumber deformation behavior under loaded fasteners. Graphs of non-dimensionalized joint yield response to fastener Ri/Ro (inside radius divided by outside radius) ratios were constructed from testing of joints fastened with 0.5 inch diameter dowels of various wall thicknesses. The graphs showed that there was no loss in Yhd/Ysd with increasing Ri/Ro until yield was primarily due to fastener buckling. The transition point in yield behavior associated with fastener yield due primarily to hollow fastener buckling can be approximated by
setting Yhd/Ysd to one across Ri/Ro, plotting the hollow fastener yield curves determined from constrained shear testing, and finding the intersection of the lines.

Determination of load corresponding to a predetermined level of deformation in the LSL was accomplished via a displaced volume method. Load displacement data obtained through dowel bearing testing of LSL was combined with the displaced volume method to predict loads at specified joint displacements. The predicted loads showed good agreement with actual loads. Application of the displaced volume approach combined with using fastener yield curves obtained through constrained shear testing make it possible to select joint components such that yield will occur primarily through fastener buckling.

**Introduction**

Reuse and recycling represent opportunities to reduce virgin raw material demands associated with construction activities (Falk and McKeever, 2004). Additionally, reuse and recycling provide a means to lower the embodied energies in structures and to increase the duration of time that carbon is retained in the built environment. However, most buildings are not designed to be disassembled and are constructed with permanent fixing methods which provide for few building removal methods other than destructive demolition (Crowther, 2001). Destructive demolition techniques damage materials and create dirty and mixed material waste streams which result in obstacles to reuse and recycling. Planning for deconstruction in the design phase of residential structures may allow for less destructive disassembly techniques for removal of residential structures after they have been used.

Calkins (2009) defines design for deconstruction as, “The design of buildings or products to facilitate future change and the eventual dismantlement (in part or whole) for recovery of
systems, components, and materials.” In planning for deconstruction and material recovery, some strategies for addressing material reuse barriers can be employed. One such strategy is to employ mechanical fasteners that are easily removable and minimize damage to the connected substrates.

Several researchers have investigated the use of hollow rivets, commonly referred to as tube fasteners, hollow fasteners, or hollow dowels, as a means to improve ductility and alleviate brittle failure in timber joints (Cruz and Ceccotti, 1996; Werner, 1996; Leijten, 1999, 2001; Leijten et al, 2004, 2006; Guan and Rodd, 2000, 2001a, 2001b; Murty, 2005; Murty et al, 2007, 2008). Use of hollow rivets for joint fasteners presents an opportunity to employ removable fasteners that can reduce bearing substrate damage resulting from deconstruction activities or design events. Through experimental testing, Olson (2011) showed that bearing substrate deformation can be reduced in lap-joints fastened with thin walled hollow fasteners as compared to similar joints fastened with solid connectors. By proper selection of rivet diameter, wall thickness, and material, it may possible to design a joint in which hollow rivets collapse before substantial deformation occurs in the bearing substrates. If joint failure is preferentially directed into the fastener, substrate damage due to design events or deconstruction activities may be reduced, leaving the building materials reusable through replacement of failed fasteners.

In order to effectively utilize hollow fasteners, an understanding of the behavior of joints fastened with hollow rivets is necessary. Previous work has featured efforts to model yield points, load-displacement relationships, and joint capacity of connections fastened with hollow fasteners. Leijten (1999) tested joints fastened with expanded steel tube fasteners in timber reinforced with densified veneer wood (DVW). In his research, 18 mm and 35 mm hollow steel tubes were inserted into slightly oversized, pre-drilled holes and then expanded to fill the hole
and impart a prestress into the wood substrates. The wood members were reinforced with DVW which was glued onto the interface surfaces between the connection members. Double shear joints were constructed and tested monotonically to determine joint characteristics. Joints constructed with DVW reinforcement and expanded steel fasteners were reported to abate brittle failure by preventing timber splitting through ductile embedment behavior of the DVW and plastic deformation of the hollow fastener. To evaluate joint load-slip performance, Leijten fit a model developed by Jaspart and Maquoi (1994) to the test data. The parameters for Jaspart’s model are graphically shown in Figure 4.1 and the model is written:

\[ F = \frac{(a - b)\delta}{1 + \left( \frac{(a - b)\delta}{c} \right)^{\frac{1}{d}}} + b\delta \]

Eqn. 4.1

Where:

- \( F \) = load per shear plane per fastener
- \( a \) = the initial stiffness
- \( b \) = the post yield stiffness
- \( c \) = the transition of elastic to semi-plastic bending moment
- \( d \) = a curve parameter
- \( \delta \) = slip or displacement
To predict joint capacity of an individual fastener, $F$, Leijten (1999) proposed the following models:

\[ F = (t_1 f_{emb, timber} + t_2 f_{emb, DVW})d \quad \text{with} \quad t_1 \leq 2t_2 \]  
\[ F = A_{st} f_t \]  

Eqn. 4.2

Eqn. 4.3

Where:

- $F$ = joint strength per fastener per shear plane and is the lesser value of the two equations
- $A_{st}$ = the cross-sectional area of the hollow fastener
- $f_t$ = the tensile strength of the hollow fastener material
- $t_1$ = the timber side member thickness
- $t_2$ = the DVW thickness
- $f_{emb, timber}$ = the embedment strength of the timber
- $f_{emb, DVW}$ = the embedment strength of the DVW
- $d$ = the outside fastener diameter

Guan and Rodd (2000, 2001a, 2001b) also performed research with joints featuring DVW reinforced timber members and hollow steel dowels. They injected resin into the space between the dowel hole and the outer edges of the dowel in order to promote immediate load take-up in the joint and eliminate joint slip associated with dowel hole clearance. Similar to the findings of Leijten (1999), Guan and Rodd (2001a) concluded that the potential advantages of joints fabricated with DVW reinforced members fastened with hollow dowels include: reduced risk of premature, brittle joint failure; improved joint ductility due to improved embedding performance; improved joint stiffness due to immediate load take-up; increased load bearing capacity; and a
greater degree of predictability of joint deformation and failure mode if failure is confined to the dowel.

In subsequent work, Guan and Rodd (2001b) created a three dimensional finite element model to simulate structural performance of a DVW reinforced timber joint fastened with a single hollow steel dowel. A moment resisting joint fastened with multiple hollow dowels was also modeled. Hollow steel dowels were assumed to be elastoplastic and wood was modeled as an orthotropic elastic material. Monotonic testing of double shear, DVW reinforced joints connected with hollow steel dowels was conducted to validate the finite element model. Guan and Rodd (2001b) reported good agreement between the predictions of large plastic shear deformation in the dowel and the physical test results. Additionally, they reported good agreement between load-slip predictions and observed load-slip test values. They concluded that a chosen combination of strength and stiffness is attainable by varying the wall thickness of hollow dowels.

Murty et al (2007) evaluated the capability of the European Yield Model (EYM), originally developed by Johansen (1949), to predict load carrying capacities of solid wood and laminated strand lumber connections employing tight-fitting steel hollow fasteners with external diameters up to 12.7 mm. They compared EYM predictions with experimental test results for arrangements with one or four fasteners loaded in double shear. They found that the EYM prediction was accurate in connections that had only a single fastener or if the joined members were made of laminated strand lumber. The EYM prediction was only accurate in joints containing a single fastener because brittle failure due to splitting in spruce connections that employed multiple fasteners resulted in low joint capacities.
While efforts have been made to model load-slip behavior and joint capacity in joints fastened with hollow connectors, there has been little research aimed at characterizing the initiation of joint yielding as controlled by fastener diameter and wall thickness. Additionally, there is a lack of published work that addresses designing joints with hollow fasteners to yield primarily through buckling of the fastener walls thereby minimizing damage to the structural wood member. The goal of this work is to establish an understanding of the mechanical relationships and yield behavior of hollow fasteners used in lap-joints. The specific objectives within this work include:

1. Determine joint yielding behavior as related to hollow dowel diameter and wall thickness, and
2. Establish a method to design lap-joints such that yield is initiated primarily through fastener buckling.

Model Development

Yield Behavior as Controlled by Diameter and Wall Thickness

Olson (2011) showed that joint behavior is dependent on the wall thickness of hollow fasteners used as connectors. In LSL joints connected with solid dowels, joint yielding occurred through deformation of the LSL. In LSL joints connected with thin walled hollow fasteners, joint yielding occurred primarily through buckling and deformation within the hollow fastener. With joints connected with fasteners of intermediate wall thicknesses, joint yielding occurred through varying degrees of fastener wall buckling and LSL deformation. Defining the point at which joint yielding is predominantly due to hollow fastener buckling is central to designing joints that yield primarily through hollow fastener buckling.
In order to analyze and compare yield behaviors across various diameter and wall thickness combinations, dependent and independent variables were non-dimensionalized and compared graphically. The dependent variable, yield load, was non-dimensionalized by dividing yield loads for joints fastened with hollow fasteners (Yhd) by average yield loads found in joints fastened with solid fasteners (Ysd) of the same diameter. The independent variable expresses both hollow fastener diameter and wall thickness in a single term by dividing the inside radius (Ri) by the outside radius (Ro).

**Hollow Fastener Selection**

Selecting components to construct a joint such that yield occurs primarily through buckling of the hollow fastener can be decomposed into two parts: determining a load that the bearing substrates can withstand without exceeding a predetermined level of deformation, and determining a hollow fastener diameter and wall thickness combination that will yield at or before the afore defined load is reached. An empirical approach to determining both components was utilized in this research.

**Hollow Fastener Yield**

Prior to initial hollow fastener testing, a mechanics of materials based model for predicting yield in diametrically loaded hollow fasteners was applied. While the model gave good predictions of yield in diametrically loaded hollow fasteners, joint testing illustrated that diametric loading and plane stress assumptions do not represent the loading conditions of the lap-joints tested in this research. Appendix A contains an explanation of the diametric loading equations and contains the associated validation test results. To describe hollow fastener yield
loads by diameter and wall thickness, quadratic equations were fit to test data using multiple regression. SigmaPlot software was used to fit quadratic equations to yield load versus wall thickness data for 0.25, 0.50, and 0.75 inch diameter hollow fasteners.

**Displaced Volume**

Initially, a mechanics of materials based modeling approach involving the resolution of contact stresses into compression, tension, and shear components was applied to predict failure in the bearing components loaded under bolts. The initial modeling approach failed to provide accurate failure predictions as it did not account for transverse stresses or localized plastic deformations, and it had assumed brittle failure would occur at yield. Appendix B contains an explanation of contact stress model. To determine target loads for the bearing materials, an empirical approach was adopted.

While reducing wood deformation during joint yielding can be achieved through the use of thin walled hollow fasteners as shown in Olson (2011), complete elimination of wood deformation is not possible. Because pilot holes for the dowels are greater in diameter than the dowels, the wood members will slip and the dowels will rotate and be in contact with a small portion of the wood during the initial stages of joint loading. As the load on the joint increases yet remains below the buckling load for the hollow dowel, the wood in contact with the dowel will deform. To estimate loads generated from a predetermined amount of deformation on the bearing surfaces at the meeting faces of the fastened joint members, dowel bearing testing was combined with a volume displacement estimation method developed by Heine (2001).

Heine (2001) developed a mechanics based approach to compute the stresses around slender and rigid bolts that incorporated elements of Yield Theory (Johansen, 1947; Hilson,
1995), and a crack model developed by Jorissen (1998). Heine’s approach to calculating loads associated with wood displacements, the Displaced Volume Method, addressed the calculations as a buoyancy problem. The Displaced Volume Method assumes wood in a fastened joint can be represented as a foundation comprised of a group of individual, independent linear springs. Assuming a foundation of independent springs, the reactive force exerted by wood on a dowel pushed into it is proportional to the displaced volume. Therefore, if the displaced volume and a foundation modulus are known, the reaction force can be calculated. Heine goes on to derive equations to calculate displaced volumes for the yield modes defined in the Yield Theory by determining points of dowel rotation defined by the Yield Theory and through application of trigonometric relationships.

![Diagram of displaced volume resulting from Mode II joint yielding](image)

**Figure 4.2.** Displaced volume resulting from Mode II joint yielding (Heine, 2001).

For application in this research, hollow dowels are assumed to be perfectly rigid up until buckling is initiated within the dowel. This type of joint yielding, illustrated in Figure 4.2, is defined as Mode II failure in the National Design Specification for Wood Construction (AF&PA, 2005), in The General Dowel Equations for Calculating Lateral Connection Values (AF&PA,
and in the Displaced Volume Method. Figure 4.3 illustrates Mode II failure and defines the quantities solved for in the Displaced Volume Method.

**Figure 4.3.** Mode II type of joint failure. Dimensions shown are used to compute the displaced volumes (Heine, 2001).
For the complete set of derivations the reader is directed to Heine (2001). For the use of Heine’s work as applied in this research, the following equations were used to determine \( \Delta_{ik} \), and \( h_{ik} \) where \( i = 1, 2 \) and \( k = 1, 2 \).

\[
h_{i1} = \frac{t_i - b_i}{2} - x_{i1}
\]

Eqn. 4.4

\[
h_{i2} = \frac{b_i + t_i}{2} - x_{i2}
\]

Eqn. 4.5

Where \( t_i \) = member thickness with \( i = 1, 2 \) and \( b_i \) is obtained using Yield Theory equations as described by Hilson (1995).

\[
x_{ik} = \frac{sl}{\tan \alpha} \quad i = 1, 2 \quad k = 1, 2
\]

Eqn. 4.6

Where \( sl = slack_i/2 \) or \( slack_p/2 \). The angle of dowel rotation, \( \alpha \), is determined from joint displacement, \( \Delta_{\text{Joint}} \), and displaced volumes by:

\[
\tan \alpha = \frac{|\Delta_{\text{Joint}}|}{\frac{b_1 + t_1}{2} + \frac{b_2 + t_2}{2}}
\]

Eqn. 4.7

and

\[
\Delta_{ik} = h_{ik} \cdot \tan \alpha
\]

Eqn. 4.8

In this work, joint displacement is:

\[
\Delta_{\text{Joint}} = \Delta_{12} + \Delta_{22} + OS
\]

Eqn. 4.9
Where $OS = \text{pilot hole diameter minus dowel diameter}$. The lengths $b_1$ and $b_2$ for Mode II failure are determined by the Yield Theory equation (Hilson, 1995):

\[ b_1 = \frac{t_1}{1 + \beta} \left( \sqrt{\beta + 2 \cdot \beta^2 \cdot \left( 1 + \frac{t_2}{t_1} + \left( \frac{t_2}{t_1} \right)^2 \right) + \beta^3 \cdot \left( \frac{t_2}{t_1} \right)^2} - \beta \cdot \left( 1 + \frac{t_2}{t_1} \right) \right) \]  
Eqn. 4.10

where

\[ b_2 = \frac{b_1}{\beta} \]  
Eqn. 4.11

with

\[ \beta = \frac{F_{\text{embed}1}}{F_{\text{embed}2}} \]  
Eqn. 4.12

In this research, both members are assumed to have the same properties thus $F_{\text{embed}1} = F_{\text{embed}2}$ and $b_1 = b_2$. Which allows Equation 4.10 to be simplified to:

\[ b_1 = \frac{1}{2} \left( -t_1 - t_2 + \sqrt{3 \cdot t_1^3 + 2 \cdot t_1 \cdot t_2 + 3 \cdot t_2^2} \right) \]  
Eqn. 4.13

In this research, the members on each side of the joint are assumed to have equal thicknesses and properties, thus:

\[ t_1 = t_2 = t_i \]  
Eqn. 4.14

\[ b_1 = b_2 = b_i \]  
Eqn. 4.15
\[ \Delta_{i2} = \Delta_{22} = \Delta_{i2} \quad \text{Eqn. 4.16} \]

\[ \Delta_{i1} = \Delta_{21} = \Delta_{i1} \quad \text{Eqn. 4.17} \]

\[ h_{i1} = h_{21} = h_{i1} \quad \text{Eqn. 4.18} \]

\[ h_{i2} = h_{22} = h_{i2} \quad \text{Eqn. 4.19} \]

Loads were predicted by selecting a predetermined amount of deformation in the LSL on the bearing surfaces at the meeting faces of the members, \( \Delta_{i2} \), and then using Equations 4.4 through 4.13 to determine values for \( \Delta_{i1} \) and \( h_{ik} \). To initiate the calculations, \( \Delta_{i2} \) was selected to be the average displacement at yield found in dowel bearing testing and the pilot hole for the dowel was assumed to be 0.03125 inches greater in diameter than the dowels. The dowel bearing yield load used in the calculations was determined through an elastic-plastic line intersection method. This dowel bearing yield load was used in place of the five percent offset yield load because it was more conservative and was associated with less permanent deformation in the bearing substrate.

Dowel bearing loads per unit length for average displacements of \( \Delta_{i2} \) and \( \Delta_{i1} \) were obtained from dowel bearing load-displacement data and used to estimate loads by assuming linear load-displacement behaviors in the displacement ranges of 0 to \( \Delta_{i2} \) and 0 to \( \Delta_{i1} \). Thus loads were predicted by:

\[ P = \frac{P_{db\Delta_{i2}} \cdot h_{i2}}{2} + \frac{P_{db\Delta_{i1}} \cdot h_{i1}}{2} \quad \text{Eqn. 4.20} \]
Where

\[ P_{db\Delta_2} = \text{dowel bearing load per linear inch at displacement } \Delta_2 \]

\[ P_{db\Delta_1} = \text{dowel bearing load per linear inch at displacement } \Delta_1 \]

**Materials and Methods**

**Joint Materials**

Hollow fasteners were from cut from extruded, seamless, round, aluminum tubes (6061-T6 alloy tubes produced by Precision Tube Co.). All solid fasteners were extracted from grade 5, hardened steel bolts. The bolt head and threaded shafts were removed with a band saw to leave a smooth solid dowel. Commercially produced laminated strand lumber (LSL) was used to fabricate all test joints. The LSL used or this work was 1.25 inch thick, 1.3E rated TimberStrand® Rimboard product manufactured in Canada by Weyerhaeuser corporation. Table 4.1 lists the diameter and wall thickness configurations tested as well and the number of samples for each test.
**Table 4.1.** Hollow fastener specimen requirements for constrained shear testing by diameter and wall thickness.

<table>
<thead>
<tr>
<th>Hollow Fastener Specifications</th>
<th>Number of Hollow Fastener Test Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Diameter (in.)</td>
<td>Nominal Wall Thickness (in.)</td>
</tr>
<tr>
<td>0.25</td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
</tr>
<tr>
<td>0.50</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>0.058</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
</tr>
<tr>
<td>0.75</td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>0.083</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
</tr>
</tbody>
</table>

**Constrained Shear Hollow Fastener Testing**

All mechanical tests performed on hollow fasteners employed a screw driven universal test machine rated for a maximum load of 30 kips. Shear loads were applied to hollow fasteners through 1 inch thick by 4 inch wide by 3 inch high steel plates that were aligned to replicate a lap-joint. Hollow fasteners were inserted in holes drilled through the steel plates. The centers of the holes were placed in the middle of the width of the plate and were located one inch from the bottom of the plate. The holes drilled through the steel plates were 1/32 inches greater in diameter than the fasteners that they were intended to accept. The test apparatus is shown in Figure 4.4.
Joint Testing

Monotonic lap-joint connection tests were conducted according to ASTM D5652-95 Standard Test Methods for Bolted Connections in Wood and Wood-Based Products. Individual test specimens consisted of two pieces of LSL whose nominal dimensions were 6 inches wide by 6 inches long by 1.04 inches thick and 6 inches wide by 14 inches long by 1.04 inches thick. In each joint test specimen, a single hollow fastener inserted through predrilled holes in each LSL piece connected the LSL components. The holes drilled through the LSL components were 1/32 inches greater in diameter than the fasteners used to connect the components.

The diameter and wall thickness combinations as well as the number of specimens tested are listed in Table 4.2. The joint test apparatus is shown in Figure 4.5. A detailed description of the materials and methods are contained in Olson (2011).
Figure 4.5. Joint testing apparatus.

Table 4.2. Sample sizes and fastener configurations for single load application lap-joint testing.

<table>
<thead>
<tr>
<th>Hollow Fastener Specifications</th>
<th>Number of Lap Joint Test Specimens (single loading)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Diameter (in.)</td>
<td>Nominal Wall Thickness (in.)</td>
</tr>
<tr>
<td>0.25</td>
<td>0.035</td>
</tr>
<tr>
<td>0.50</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>0.058</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
</tr>
<tr>
<td>0.75</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Dowel Bearing

Dowel bearing testing was performed in accordance with ASTM D 5764-97a using the half hole configuration. Test specimens were nominally 3 inches wide by 3 inches tall, and 1.25 inches thick. The predrilled hole was 1/32 inches greater in diameter than the dowel used in
testing. All dowel bearing tests were performed on a screw driven universal test machine rated for a maximum load of 30 kips. Digital data acquisition equipment recorded data from a 30 kip load cell and an internal encoder. The crosshead speed used with 0.5 and 0.75 inch diameter dowels was 0.04 inches per minute. The crosshead speed used with 0.25 inch diameter dowels was 0.02 inches per minute.

Yield loads were determined using the five percent offset method specified in ASTM D 5764-97a as well as through an elastic-plastic line intersection method. The elastic-plastic intersection method involved locating the intersection of a line projected along the linear elastic range of the load-displacement test data curve and a line projected along the load-displacement test data curve after yield had occurred. The intersection of the lines marked the deflection at yield and the load was read directly from the load-displacement test data.

**Statistical Methods**

Regression analyses were performed on the constrained shear test results using SigmaPlot software. Statistical tests were also used to interpret joint test data. The tests identified the existence of significant differences in yield loads and factors that significantly influenced yield. The analysis tool used with the joint test results was an analysis of covariance (ANCOVA) and Duncan’s multiple range test to identify mean differences. The statistical tests were compared with a significance of 0.05 and were completed using SAS software.
Results and Discussion

Constrained Shear Hollow Fastener Test Results

Yield loads for hollow fasteners tested in the constrained shear test fixture are listed in Table 4.3. For a fixed diameter, yield load increased with increasing wall thickness. Over the range of wall thickness and diameter combinations tested, the increase in yield load varied in a non-linear manner with increasing thickness (Figure 4.6). Quadratic equations were fit to the test data through a least-squares means approach performed with SigmaPlot software. The quadratic equation constants and $R^2$ values are listed in Table 4.3 and the predicted values calculated with the equations are graphed with the test data in Figure 4.6.
Table 4.3. Constrained shear test results.

<table>
<thead>
<tr>
<th>Nominal Outside Diameter (in.)</th>
<th>Nominal Wall Thickness, w (in.)</th>
<th>Ri/Ro</th>
<th>Constrained Shear Test, Yield Load (lb) (%COV)</th>
<th>Regression fit to Quadratic Equation (Yield = Y_0 + a \cdot w + b \cdot w^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.035</td>
<td>0.72</td>
<td>508 (2.96) 833 (1.40) 969 (1.60)</td>
<td>-1140 64189 -488392 0.995</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>0.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>0.028</td>
<td>0.89</td>
<td>696 (2.80) 933 (2.28) 1406 (2.29) 1611 (1.61)</td>
<td>-368 40631 -97245 0.994</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>0.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.058</td>
<td>0.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>0.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.75</td>
<td>0.035</td>
<td>0.91</td>
<td>1227 (4.06) 3754 (2.79) 4699 (2.35)</td>
<td>-1588 92134 -334732 0.996</td>
</tr>
<tr>
<td></td>
<td>0.083</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0.67</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lap-Joint Test Results

In test joints fastened with 0.5 inch diameter dowels that had the LSL oriented either parallel (parallel joints) or perpendicular (perpendicular joints) to the direction of load, yield loads did not decrease with decreasing wall thickness until the mode of yield was dominated by hollow fastener buckling. Change in the mode of yield was evident visually as hollow fastener distortion increased while deformation in the LSL decreased. Additionally, the shift in yield mode was accompanied with a marked drop in the coefficients of variation (COV) in the yield load. The decrease in the yield load COV’s was due to energy absorption being concentrated in the fasteners which resulted in more consistent yield loads due to the much higher degree of homogeneity in metals compared to that of wood and wood products. In both LSL orientations, parallel and perpendicular, joint yielding was dominated by fastener buckling in 0.5 inch diameter hollow fasteners with 0.035 inch and 0.028 inch thick walls.
Table 4.4. Yield load in lap joints fastened with hollow and solid fasteners.

<table>
<thead>
<tr>
<th>Nominal Fastener Diameter (in.)</th>
<th>Nominal Wall Thickness for Hollow Dowels</th>
<th>Ri/Ro</th>
<th>Yield Loads for Parallel Joints (lb) (%COV)</th>
<th>Yield Loads for Perpendicular Joints (lb) (%COV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.035</td>
<td>0.72</td>
<td>437 (16.0)</td>
<td>399 (14.4)</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0</td>
<td>382 (24.8)</td>
<td>331 (18.1)</td>
</tr>
<tr>
<td>0.50</td>
<td>0.028</td>
<td>0.89</td>
<td>686 (6.4)</td>
<td>707 (2.7)</td>
</tr>
<tr>
<td></td>
<td>0.035</td>
<td>0.86</td>
<td>893 (5.20)</td>
<td>891 (3.50)</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>0.80</td>
<td>1150 (21.10)</td>
<td>893 (13.90)</td>
</tr>
<tr>
<td></td>
<td>0.058</td>
<td>0.77</td>
<td>1035 (16.50)</td>
<td>842 (24.70)</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>0.74</td>
<td>1025 (14.80)</td>
<td>837 (15.9)</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0.50</td>
<td>1139 (20.00)</td>
<td>790 (16.60)</td>
</tr>
<tr>
<td></td>
<td>0.250</td>
<td>0</td>
<td>1006 (12.1)</td>
<td>734 (24.6)</td>
</tr>
<tr>
<td>0.75</td>
<td>0.035</td>
<td>0.91</td>
<td>1240 (4.0)</td>
<td>1290 (7.3)</td>
</tr>
<tr>
<td></td>
<td>0.375</td>
<td>0</td>
<td>1304 (12.0)</td>
<td>1065 (16.3)</td>
</tr>
</tbody>
</table>

To characterize joint behavior across different fastener diameters and wall thicknesses on a non-dimensional basis, the relationship between wall thickness and hollow fastener diameter was expressed as the ratio of the fastener inside diameter (Ri) divided by the fastener outside diameter (Ro). To non-dimensionalize yield loads, average yield loads for joints connected with hollow fasteners (Yhd) of a given diameter-wall thickness combination and LSL orientation were divided by the average yield load found in joints connected with a solid fastener (Ysd) of the same diameter and with the same LSL orientation. Figures 4.7 and 4.8 show the joint yielding behavior for joints connected with 0.5 inch diameter fasteners.
Figure 4.7. $R_i/R_o$ versus $Y_{hd}/Y_{sd}$ in joints fastened with 0.5 inch diameter dowels which had the LSL oriented parallel to the applied load.

Figure 4.8. $R_i/R_o$ versus $Y_{hd}/Y_{sd}$ in joints fastened with 0.5 inch diameter dowels which had the LSL oriented perpendicular to the applied load.
In parallel and perpendicular joints fastened with 0.5 inch diameter dowels, joint yielding was dominated by fastener buckling in 0.5 inch diameter hollow fasteners with 0.035 inch and 0.028 inch thick walls. Parallel and perpendicular joints connected with 0.5 inch diameter fasteners with walls thicker than 0.035 inches yielded through various amounts of fastener and LSL deformation. Because there was an obvious change in the mechanism governing joint yielding, statistical analysis of the data obtained from joints fastened with 0.5 inch diameter fasteners was performed on segregated data. Data obtained from joints connected with 0.5 inch diameter fasteners that had 0.035 inch and 0.028 inch thick walls was separated from the remainder of the data obtained from testing joints fastened with 0.5 inch diameter dowels. Data from parallel joints was analyzed separately from the data obtained from perpendicular joints. Both sets of data were analyzed through analysis of covariance (ANCOVA) with wall thickness as the independent variable, apparent specific gravity of the material removed for the dowel hole as the covariate, and yield load as the independent variable. The results of the ANCOVA for the lap joints are in Table 4.5.
Table 4.5. ANCOVA results for lap joints.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Degrees of Freedom</th>
<th>F-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>5</td>
<td>25.20</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1</td>
<td>96.31</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Ri/Ro</td>
<td>4</td>
<td>7.42</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Ri/Ro Means Test Grouping
- 0.80 A
- 0.77 A
- 0.74 B
- 0.50 B
- 0.00 C

<table>
<thead>
<tr>
<th>Variable</th>
<th>Degrees of Freedom</th>
<th>F-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>5</td>
<td>11.41</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1</td>
<td>44.88</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Ri/Ro</td>
<td>4</td>
<td>3.04</td>
<td>0.0248</td>
</tr>
</tbody>
</table>

Ri/Ro Means Test Grouping
- 0.80 A
- 0.77 A
- 0.74 A B
- 0.50 B
- 0.00 B

Note: Duncan’s multiple range test was used to determine which means were statistically different. Wall thicknesses with common letters are not statistically different while thicknesses assigned different letters are statistically different.

To clarify the statistical analysis, Figures 4.9 and 4.10 graphically show the yield means adjusted via the ANCOVA to remove variation in yield loads caused by apparent LSL specific gravity. Results from the statistical analysis of yield load data obtained from testing of parallel and perpendicular joints show some statistical differences between the means. The analysis indicates a trend of increasing yield load with decreasing wall thickness right before the yield mode switches to being dominated primarily by fastener buckling. The cause of this increase is unclear but it may be related to a match in deformation characteristics between the dowel and
LSL that minimizes stress concentrations that could initiate plastic deformation or crack initiation in the LSL at lower loads. Leijten (1999), as well as Guan and Rodd (2001a), attributed a decrease in brittle joint failure in joints fastened with hollow fasteners to ductility and deformation in the hollow fasteners that absorbed energy and inhibited fracture in the wood substrates.

![Graph](image.png)

**Figure 4.9.** Ri/Ro versus adjusted Yhd/Ysd in joints fastened with 0.5 inch diameter dowels that had the LSL oriented parallel to the applied load. The Yhd/Ysd values are the statistically adjusted means where the influence of LSL specific gravity has been removed from the means through ANCOVA.
Figure 4.10. Ri/Ro versus adjusted Yhd/Ysd in joints fastened with 0.5 inch diameter dowels that had the LSL oriented perpendicular to the applied load. The Yhd/Ysd values are the statistically adjusted means where the influence of LSL specific gravity has been removed from the means through ANCOVA.

Additional joints of both LSL orientations, which were fastened with solid 0.25 inch and 0.75 inch diameter dowels as well as hollow dowels that were 0.25 inches in diameter with 0.035 inch thick walls and 0.75 inch diameter dowels with 0.035 inch walls, were tested. The 0.035 inch wall thicknesses were chosen for both 0.25 inch and 0.75 inch diameters as they were the thinnest walls available for those diameters in aluminum 6061-T6 seamless tubes at the time of testing. Yield in joints fastened with 0.75 inch diameter dowels with the 0.035 inch walls was dominated by fastener buckling in the parallel and perpendicular LSL orientations. Yield in the joints connected with the 0.25 diameter fasteners with 0.035 inch thick walls was primarily due to wood deformation with some minor deformation in the hollow fastener. Figures 4.11 and 4.12 show average yield loads for the joints connected with 0.25 and 0.75 inch diameter hollow fasteners plotted along side the adjusted yield loads (for Ri/Ro ratios between 0-0.802) obtained
from joints connected with 0.5 inch hollow fasteners. Additionally, extrapolated hollow fastener yield predictions, calculated from the equations fit to the constrained shear test data, were divided by the average yield loads found in joints connected with a solid fastener (Ysd) of the corresponding diameter and LSL orientation and graphed in Figures 4.11 and 4.12.

**Figure 4.11.** Ri/Ro versus adjusted Yhd/Ysd in parallel joints with the regression predictions for constrained hollow fastener shear overlaid. Note: the Yhd/Ysd values for Ri/Ro 0-0.8 have been adjusted to remove LSL specific gravity effects via ANCOVA.
Figure 4.12. Ri/Ro versus adjusted Yhd/Ysd in perpendicular joints with the regression predictions for constrained hollow fastener shear overlaid. Note: the Yhd/Ysd values for Ri/Ro 0-0.8 have been adjusted to remove LSL specific gravity effects via ANCOVA.

Figures 4.11 and 4.12 show that joint yield loads can be predicted from equations fit to hollow fastener constrained shear test data when joint yielding is primarily due to fastener buckling. All the average joint yield loads obtained from joints where joint yielding was primarily due to fastener buckling fall on the constrained hollow fastener yield prediction curves. Additionally, data points obtained from joints where yield was due to LSL deformation or a combination of fastener and LSL deformation fall to the left of the corresponding hollow fastener yield prediction curves as expected. However, Figures 4.11 and 4.12 show that the location of the intersection of the fastener yield predictions with the joint yield data, obtained from joints connected with 0.5 inch diameter fasteners, is dependent on fastener diameter. Therefore, it is apparent that exact joint behavior determined from joints fastened with connectors of a single
diameter but a variety of wall thicknesses cannot be extrapolated to predict specific $Y_{hd}/Y_{sd}$ responses to $R_i/R_o$ ratios in joints connected with different diameter fasteners.

The influence of dowel diameter between the hollow fastener yield curves can be partially explained through the mechanics used to describe stress in diametrically loaded rings. In Chapter 3 it was determined that diametric loadings do not completely replicate the conditions in lap-joints due to multi-axial stresses and the lateral constraint. However, at large $R_i/R_o$ ratios, such as those seen where the hollow fastener yield curves intersect the joint data in Figures 4.11 and 4.12, the diametric load behavior shown in Chapter 3 parallels that of constrained shear behavior with respect to yield responses relative to changes in wall thickness. Therefore, the equations used to determine stress in diametrically loaded hollow fasteners can be used to partially explain the diameter dependence seen between the hollow fastener yield curves generated through the constrained shear testing.

Nelson (1939) used elastic theory and a mechanics of materials approach to derive equations to calculate stresses in diametrically loaded rings of varying diameter and wall thicknesses. Nelson’s equation for stress on the inner boundary, \( \sigma_\theta \), of a diametrically loaded ring is:

\[
\left( \sigma_\theta \right)_i = -M_o \frac{P}{\pi R_o t} + \frac{P}{\pi R_o t} \left( -M_2 \cos 2\theta^* + M_4 \cos 4\theta^* - M_6 \cos 6\theta^* + ... \right)
\]

Eqn. 4.21

and the equation for stress on the outer boundary, \( \sigma_\theta \), of a diametrically loaded ring is:

\[
\left( \sigma_\theta \right)_o = \frac{M' P}{\pi R_o t} - M_o' \frac{P}{\pi R_o t} + \frac{P}{\pi R_o t} \left( M_2' \cos 2\theta^* - M_4' \cos 4\theta^* + M_6' \cos 6\theta^* + ... \right)
\]

Eqn. 4.22
Where

\[ M' = 1 \text{ when } \theta' = \frac{\pi}{2} \text{ or } \frac{3\pi}{2} \]  
Eqn. 4.23

\[ M' = 0 \text{ when } \theta' \neq \frac{\pi}{2} \text{ or } \frac{3\pi}{2} \]  
Eqn. 4.24

\[ M_0 = \frac{2}{(1 - \alpha^2)} \]  
Eqn. 4.25

\[ M_0' = \frac{2\alpha^2}{(1 - \alpha^2)} \]  
Eqn. 4.26

\[ \alpha = \frac{R_i}{R_o} \]  
Eqn. 4.27

\[ M_n = \frac{4n\alpha^{n-2}(1 - \alpha^2)(1 - \alpha^{2n})}{Q_n} \quad \text{for } n=2, 4, 6, \ldots \]  
Eqn. 4.28

\[ M_n' = \frac{4(1 - \alpha^2)^2}{\alpha^2} \frac{n^2\alpha^{2n}}{Q_n} \quad \text{for } n=2, 4, 6, \ldots \]  
Eqn. 4.29

\[ Q_n = (1 - \alpha^{2n})^2 - n^2\alpha^{2n-2}(1 - \alpha^2)^2 \]  
Eqn. 4.30

\( t = \) thickness of the ring, \( P, \ R_i, \ R_o, \) and \( \theta' \) are as defined in Figure 4.13.
For the sake of simplifying the explanation, assume there is a critical stress that once reached on the inside and/or outside edge of a diametrically loaded hollow fastener, the fastener yields. Setting Equation 4.21 or Equation 4.22 equal to this critical stress and then fixing all variables except $P$ and $Ro$, it becomes apparent from examination of Equations 4.21 and 4.22 that $P$ must increase with increasing $Ro$. The relationship between this critical stress with $P$ and $Ro$ accounts for some of the differences seen between the hollow fastener yield prediction curves in Figures 4.11 and 4.12.

While the exact Yhd/Ysd response to a given $Ri/Ro$ cannot be determined though extrapolation between fastener diameters, it is reasonable to expect the general form of the relationship to hold across different fastener diameters. The joint behavior seen in Figures 4.11 and 4.12 show that there is no loss in Yhd/Ysd with increasing $Ri/Ro$ until yield is primarily due to fastener buckling. If the increase in Yhd/Ysd seen near the transition to fastener buckling controlled joint yielding is ignored, then Yhd/Ysd can be assumed to be constant across $Ri/Ro$ until joint yielding is due primarily to fastener buckling. Such an assumption would be conservative for $Ri/Ro$ ratios near the transition to hollow fastener buckling controlled joint
yielding. Figures 4.14 and 4.15 show a constant \( \frac{Y_{hd}}{Y_{sd}} \) intersected by the hollow fastener yield curves determined through constrained shear testing. Creating a joint in which joint yielding will be initiated through fastener buckling can be accomplished by selecting a fastener diameter and a \( \frac{R_i}{R_o} \) ratio from the graph that is equal to or greater than the \( \frac{R_i}{R_o} \) at the intersection between the constant \( \frac{Y_{hd}}{Y_{sd}} \) response and the appropriate hollow fastener yield curve.

**Figure 4.14.** Constant \( \frac{Y_{hd}}{Y_{sd}} \) versus \( \frac{R_i}{R_o} \) in parallel joints with the regressions from unconstrained shear extrapolated and overlaid.
Figure 4.15. Constant Yhd/Ysd versus Ri/Ro in perpendicular joints with the regressions from unconstrained shear extrapolated and overlaid.

**Displaced Volume Load Estimates**

Table 4.6 contains dowel bearing test results. Yield loads and displacements determined by the elastic-plastic line intersection were used in the displaced volume load estimates. These were used in place of the five-percent offset results in order to minimize LSL deformation as both yield loads and displacements as determined through the elastic-plastic line intersection method were more conservative. Calculation inputs and predicted loads used in the displaced volume approach are shown in Table 4.7.
Table 4.6. Dowel bearing test results.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Yield Stress by 5% Offset (psi) (COV%)</th>
<th>Displacement at Yield by 5% Offset (in.) (COV%)</th>
<th>Yield Stress by Elastic-Plastic Intersection (psi) (COV%)</th>
<th>Displacement at Yield by Elastic-Plastic Intersection (psi) (COV%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75”</td>
<td>5572 (17.35)</td>
<td>0.0707 (6.63)</td>
<td>5105 (18.0)</td>
<td>0.0335 (14.92)</td>
</tr>
<tr>
<td>Dia. Dowel, Parallel LSL Orient.</td>
<td>4591 (16.93)</td>
<td>0.0906 (9.54)</td>
<td>3883 (18.71)</td>
<td>0.0548 (17.07)</td>
</tr>
<tr>
<td>0.50”</td>
<td>5676 (23.15)</td>
<td>0.0600 (12.28)</td>
<td>5033 (23.60)</td>
<td>0.0306 (21.28)</td>
</tr>
<tr>
<td>Dia. Dowel, Parallel LSL Orient.</td>
<td>4869 (22.10)</td>
<td>0.0745 (8.28)</td>
<td>4100 (23.35)</td>
<td>0.0497 (16.01)</td>
</tr>
<tr>
<td>0.25”</td>
<td>6716 (14.67)</td>
<td>0.0379 (12.68)</td>
<td>6011 (13.99)</td>
<td>0.0270 (18.98)</td>
</tr>
<tr>
<td>Dia. Dowel, Parallel LSL Orient.</td>
<td>5232 (17.42)</td>
<td>0.0474 (7.32)</td>
<td>4414 (18.70)</td>
<td>0.0346 (12.12)</td>
</tr>
<tr>
<td>0.25”</td>
<td>0.50” Dia. Dowel, Perpendicular LSL Orient.</td>
<td>0.0335 (14.92)</td>
<td>0.0548 (17.07)</td>
<td>0.0306 (21.28)</td>
</tr>
<tr>
<td>Dia. Dowel, Perpendicular LSL Orient.</td>
<td>0.0497 (16.01)</td>
<td>0.0270 (18.98)</td>
<td>0.0346 (12.12)</td>
<td>0.0270 (18.98)</td>
</tr>
<tr>
<td>0.50”</td>
<td>0.75” Dia. Dowel, Parallel LSL Orient.</td>
<td>0.0497 (16.01)</td>
<td>0.0270 (18.98)</td>
<td>0.0346 (12.12)</td>
</tr>
<tr>
<td>0.75”</td>
<td>0.50” Dia. Dowel, Parallel LSL Orient.</td>
<td>0.0306 (21.28)</td>
<td>0.0270 (18.98)</td>
<td>0.0346 (12.12)</td>
</tr>
<tr>
<td>Dia. Dowel, Parallel LSL Orient.</td>
<td>0.0497 (16.01)</td>
<td>0.0270 (18.98)</td>
<td>0.0346 (12.12)</td>
<td>0.0270 (18.98)</td>
</tr>
<tr>
<td>0.25”</td>
<td>0.25” Dia. Dowel, Parallel LSL Orient.</td>
<td>0.0306 (21.28)</td>
<td>0.0270 (18.98)</td>
<td>0.0346 (12.12)</td>
</tr>
<tr>
<td>Dia. Dowel, Parallel LSL Orient.</td>
<td>0.0497 (16.01)</td>
<td>0.0270 (18.98)</td>
<td>0.0346 (12.12)</td>
<td>0.0270 (18.98)</td>
</tr>
</tbody>
</table>
Predicted and actual loads are listed in Table 4.8. Overall, the predicted loads, with slack equal to 1/64 inch, show good agreement with actual loads. The parallel joints fastened with the 0.5 inch diameter dowels with 0.028 inch thick walls had lower actual yield loads than predicted because the fasteners buckled before the predicted load could be reached. In every case where
slack was set equal to 0.015625, except for parallel joints fastened with 0.5 inch diameter dowels with 0.028 inch thick walls, the actual loads were slightly higher than predicted loads. The consistent difference between predicted loads, where slack was set equal to 0.015625, and actual loads likely lies in the assignment of slack values. It is impossible to know the exact slack values prior to loading (Heine, 2001). Due to the lack of exact knowledge of the slack values prior to loading, slack was assigned as half of the difference between the dowel diameter and the pilot hole diameter. Changing slack values to zero altered the predicted loads such that they were consistently greater than the actual loads (Table 4.8). As the actual loads lie between the predictions obtained with slack set to zero and slack set to 1/64 inches, refinement of the predictions may be achieved through better quantification of the actual initial slack values.
Table 4.8. Actual loads in joint testing versus loads predicted using the Displaced Volume Method at select joint displacement, $\Delta_{\text{joint}}$.

<table>
<thead>
<tr>
<th>LSL Orientation</th>
<th>Dowel Diameter (in.)</th>
<th>Dowel Wall Thickness (in.)</th>
<th>Target Joint Displacement, $\Delta_{\text{joint}}$, (in.)</th>
<th>Actual Joint Load at $\Delta_{\text{joint}}$, (lbs) (COV%)</th>
<th>Predicted Joint Load at $\Delta_{\text{joint}}$, with $s_l = 1/64''$ (lbs)</th>
<th>Predicted Joint Load at $\Delta_{\text{joint}}$, with $s_l = 0$ (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>0.25</td>
<td>0.035 0.125</td>
<td>0.0853</td>
<td>408 (14.5) 410 (26.4)</td>
<td>349 502</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.028 0.035 0.049 0.058 0.065 0.125 0.250</td>
<td>0.0925</td>
<td>593 (10.3) 707 (5.8) 798 (19.6) 805 (11.8) 779 (15.2) 870 (19.8) 904 (11.2)</td>
<td>617 837</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0.035 0.375</td>
<td>0.0983</td>
<td>1001 (7.8) 1128 (12.0)</td>
<td>974 1382</td>
<td></td>
</tr>
<tr>
<td>Perpendicular</td>
<td>0.25</td>
<td>0.035 0.125</td>
<td>0.1005</td>
<td>364 (17.5) 311 (18.1)</td>
<td>284 392</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.028 0.035 0.049 0.058 0.065 0.125 0.250</td>
<td>0.1307</td>
<td>642 (5.2) 765 (10.8) 713 (9.3) 692 (21.4) 760 (14.7) 630 (14.8) 629 (13.9)</td>
<td>604 738</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0.035 0.375</td>
<td>0.1409</td>
<td>999 (9.1) 927 (14.9)</td>
<td>903 1070</td>
<td></td>
</tr>
</tbody>
</table>

An overview of the method for selecting components to design a joint to yield primarily due to fastener collapse can be summarized by the following steps:

1. Select a fastener diameter,
2. Use the displaced volume method to estimate to determine a maximum load for the bearing material,
3. Input the load for the bearing material into the constrained shear regression equation and solve for wall thickness. Solving for the wall thickness provides the
value of the thickest fastener wall that can be used and still produce a joint where yield occurs primarily through fastener collapse,

**Summary and Conclusions**

Three types of yield behavior were evident in visual examination of tested joints. In joints fastened with solid dowels, joint yielding resulted from deformation in the LSL and rigid dowel rotation. In joints connected with hollow dowels with very thin walls, joint yielding was primarily due to deformation in the dowel with little LSL deformation. Yield in joints connected with hollow dowels, which fell between very thin walled and very thick walled, resulted from a combination of the LSL and dowel deformation.

Graphs of non-dimensionalized joint yield response to fastener Ri/Ro ratios were constructed from testing of joints fastened with 0.5 inch diameter dowels of various wall thicknesses. Hollow fastener yield curves for fasteners of different diameters were overlaid on the Yhd/Ysd vs. Ri/Ro graphs for 0.5 inch diameter dowels. It is apparent that hollow fastener yield loads are dependent on diameter as well as the Ri/Ro ratio. Because of the effect of diameter on fastener yield, Yhd/Ysd vs. Ri/Ro behavior for joints connected with 0.5 inch diameter dowels cannot be generalized to joints fastened with connectors of other diameters in order to find transition points in yield behavior.

While the exact Yhd/Ysd response to a given Ri/Ro cannot be determined though extrapolation between fastener diameters, it is reasonable to expect the general form of the relationship to hold across different fastener diameters. The joint behavior seen in Figures 4.11 and 4.12 show that there is no loss in Yhd/Ysd with increasing Ri/Ro until yield is primarily due to fastener buckling. Thus the transition point in yield behavior associated with fastener yield
due primarily to hollow fastener buckling can be approximated by setting $Y_{hd}/Y_{sd}$ to one across $R_i/R_o$, plotting the hollow fastener yield curves determined from constrained shear testing, and finding the intersection of the lines. Joints connected with fasteners that have a $R_i/R_o$ ratio equal to or greater than that of the intersection point should yield primarily due to fastener buckling.

Determination of a load that corresponds to a selected level of deformation in the LSL can be accomplished via a displaced volume method developed by Heine (2001). Load displacement data obtained through dowel bearing testing of LSL was combined with the displaced volume method to predict loads at specified joint displacements. The predicted loads showed good agreement with actual loads in LSL lap-joints fastened with a variety of hollow and solid fasteners.

Because an empirical modeling approach was used, application of the model is limited to the conditions, parameters, and joint configurations employed in this research. Using substrate materials that are thinner than those used here or using pilot holes greater than those used here will result in greater dowel rotation prior to the build up of loads in the joint. Increased dowel rotation will alter the load scenario in the dowel and is likely to result in joint behavior different than what was observed in this work. Likewise, joints constructed with materials that have different properties than the LSL used here are likely to result in different joint behaviors.

Future research should be focused on expanding this model to account for joints that are asymmetric in regards to bearing material properties and dimensions. Additionally, research incorporating the impact of end fixity and multiple fastener configurations on fastener collapse and joint capacity should be pursued.
References


CHAPTER FIVE

Project Summary/Conclusion

Extending the service life of building materials through reuse presents an opportunity to address sustainable development through reducing material and energy demands. To extend the service life of building products, it is necessary to understand the current use and service life of materials used in structures. Additionally it is apparent that the application of design for deconstruction concepts combined with a fastening methodology that enables deconstruction while reducing design event and deconstruction damage is required.

This research begins to fill the gap in service life knowledge by providing service life predictions of structures built with current materials and construction techniques. The service life of residential structures in the U.S. was predicted by employing previous models and model fits to housing inventory data. Housing inventory data obtained from U.S. census housing surveys was used to build housing age distributions. Weibull and Gompertz curves were fit to the distributions and used to predict service life. The average service life of residential structures was predicted to be between 99 and 110 years. The service life of difficult to access and replace building materials is provided assuming their service life is the same as the structure they are used in.

The concept of using hollow fasteners to provide joint ductility and reduce brittle failure was extended to provide a means to reduce damage in bearing materials. The reduction in damage to bearing materials was pursued as a means to enable building material reuse and
structure repair. An understanding of the behavioral characteristics of joints connected with hollow fasteners was developed through subjecting fasteners to various shear loadings in test fixtures as well as in lap-joints. Experimental results obtained from monotonic testing of LSL lap joints fastened with hollow and solid fasteners showed that deformation in bearing materials can be reduced when thin walled hollow fasteners are used.

The joint behavior information was used to establish a method to design lap-joints such that yield is initiated primarily through fastener buckling. Empirical models were applied to test data to describe hollow fastener yield behavior and laminated strand lumber deformation behavior under loaded fasteners. Graphs of joint yield response to fastener wall thicknesses were constructed from the testing of joints fastened with hollow dowels. The graphs showed that there was no loss in yield load with decreasing wall thickness until yield was primarily due to fastener buckling. The transition point in yield behavior associated with fastener yield due primarily to hollow fastener buckling can be approximated finding the intersection of substrate yield loads with the curve of hollow fastener yield load as determined from constrained shear testing.

Determination of load corresponding to a predetermined level of deformation in the LSL was accomplished via a displaced volume method. The displaced volume predicted loads showed good agreement with actual loads. Application of the displaced volume approach combined with using fastener yield curves obtained through constrained shear testing make it possible to select joint components such that yield will occur primarily through fastener buckling.
APPENDIX
Appendix A. Diametric Loading Model

Introduction

Test results in Chapter 3 show that the yield behavior of monotonically loaded lap-joints connected with hollow fasteners can be characterized along a continuum where extremes in behavior are defined by wall thickness of the hollow fasteners. In LSL joints connected with solid dowels, joint yield occurred through deformation of the LSL. In LSL joints connected with hollow tubes with very thin walls, joint yield occurred primarily through buckling and deformation within the hollow fastener. Between behaviors of the extremes, joint yield occurred through varying degrees of fastener wall buckling and LSL deformation. Defining the point at which joint yield is predominantly due to tube buckling is necessary to enable designing joints that yield primarily through tube buckling.

The process of selecting components to construct a lap-joint such that yield occurs primarily through buckling of the hollow fastener can be split into two parts: determining a load that the bearing substrates can withstand without exceeding a predetermined level of deformation, and determining a tube diameter and wall thickness combination that will yield at or before a defined load is reached. This appendix discusses an attempt to employ a mechanics of materials based modeling approach to predict failure in hollow fasteners used to connect LSL components.

Model Development

To model a hollow fastener being monotonically loaded in a lap-joint, plane stress conditions were assumed and the opposing loads were assumed to be point loads located directly opposite one another. Under those assumptions, the hollow fastener was modeled as a
diametrically loaded ring. Nelson (1939) used elastic theory and a mechanics of materials approach to derive equations to calculate stresses in diametrically loaded rings of varying diameters and wall thicknesses. Nelson’s equation for stress on the inner boundary, $\left(\sigma_0^i\right)$, of a diametrically loaded ring is:

$$\left(\sigma_0^i\right) = -M_o \frac{P}{\pi R_o t} + \frac{P}{\pi R_o t} \left(-M_2 \cos 2\theta^* + M_4 \cos 4\theta^* - M_6 \cos 6\theta^* + \ldots\right)$$

Eqn. A.1

and the equation for stress on the outer boundary, $\left(\sigma_0^o\right)$, of a diametrically loaded ring is:

$$\left(\sigma_0^o\right) = M'_o \frac{P}{\pi R_o t} - M'_o \frac{P}{\pi R_o t} \left(M_2' \cos 2\theta^* - M_4' \cos 4\theta^* + M_6' \cos 6\theta^* \ldots\right)$$

Eqn. A.2

Where

$M' = 1$ when $\theta^* = \pi/2$ or $3\pi/2$

Eqn. A.3

$M' = 0$ when $\theta^* \neq \pi/2$ or $3\pi/2$

Eqn. A.4

$$M_0 = \frac{2}{(1 - \alpha^2)}$$

Eqn. A.5

$$M'_0 = \frac{2\alpha^2}{(1 - \alpha^2)}$$

Eqn. A.6

$$\alpha = \frac{R_i}{R_o}$$

Eqn. A.7

$$M_n = \frac{4n\alpha^{n-2} \left(1 - \alpha^2\right)^{n-1}}{Q_n} \text{ for } n=2, 4, 6, \ldots$$

Eqn. A.8
\[ M_n = \frac{4(1 - \alpha^2)^2 n^2 \alpha^{2n}}{Q_n} \quad \text{for } n=2, 4, 6, \ldots \quad \text{Eqn. A.9} \]

\[ Q_n = (1 - \alpha^{2n})^2 - n^2 \alpha^{2n-2}(1 - \alpha^2)^2 \quad \text{Eqn. A.10} \]

\( t \) = thickness of the ring, \( P, R_i, R_o \), and \( \theta^* \) are as defined in Figure A.1.

![Figure A.1](image)

**Figure A.1.** Geometry and loading of the ring (Durelli and Lin, 1986).

Stress in diametrically loaded rings was calculated using equations A.1 through A.10. To determine a point of failure, a maximum stress failure criterion was employed.

**Materials & Methods**

All materials, equipment, and test methods used in determining yield loads in diametrically loaded tubes were as described in Chapter 3. All mathematical modeling was performed using MATLAB software.
Number of Expansion Terms

Nelson’s equations for stress in diametrically loaded rings contain series expansions. To ease the calculations of stress and strain in diametrically loaded rings, Durelli and Lin (1986) employed Nelson’s equations to construct a series of graphs containing stress factors as functions of ring geometry. In employing Nelson’s equations, Durelli and Lin used sixty terms in the series expansions but commented that more terms may be needed at certain locations along the ring. To determine the number of expansion terms required in this work, a program was written to calculate stress as a function of the number of expansion terms for a fixed loading with fixed ring diameter and wall thickness. The program was run for all combinations of tube wall thicknesses and diameters tested. Yield loads determined in testing were used as the loads in the program. The behavior of the stress calculations, as related to the number of expansion terms, was consistent across the various wall thickness-ring diameter combinations examined. Figures A.2 and A.3 show the relationship between calculated stress and the number of expansion terms used in the calculations. In the locations where stress was calculated, the calculated stress value became stable by the time twenty-five terms were used in the expansions. For all stress calculations performed in this work, twenty-five expansion terms were used in the equations.
Figure A.2. Calculated stress vs. the number of terms used in the series expansion. (Stress on the inside edge of the ring with $\theta^* = 90^\circ$)

Figure A.3. Calculated stress vs. the number of terms used in the series expansion. (Stress on the inside edge of the ring with $\theta^* = 90^\circ$)
Results and Discussion

Table A.1 contains actual and predicted yield loads. In diametrically loaded rings, the point of highest stress is located on the inside of the ring at $\theta^* = 90^\circ$ (Nelson, 1939; Durelli and Lin, 1986; Young, 1989). Initially, it was assumed that once the point on the inside of the ring at $\theta^* = 90^\circ$ reached the yield stress that the ring would become unstable and yield would result. Testing proved this to be an incorrect assumption. Examination of the stress states on both the inside and outside edges of the ring, for $\theta^* = 0^\circ$ to $90^\circ$, showed that for rings with high $R_i/R_o$ ratios, the ring became unstable and yielded once the yield stress was reached on the outside edge at $\theta^* = 0$. Yield load predicted at the outside edge of a ring at $\theta^* = 0$ was indicative of tube yield only for thin walled tubes (Figure A.3). The data indicates that as wall thickness increases, the mechanism controlling tube yield changes as the curve of the yield load for the outside edge of the ring $\theta^* = 0^\circ$ departs from actual yield loads (Figure A.3).

Table A.1. Actual and predicted yield loads in diametrically loaded tubes.

<table>
<thead>
<tr>
<th>Outside Diameter</th>
<th>Nominal Wall Thickness</th>
<th>Ri/Ro</th>
<th>Yield Load (lbs/in)</th>
<th>Predicted Yield Load at $\theta^*=0^\circ$ on the Outside Edge of the Ring (lbs/in.)</th>
<th>Predicted Yield Load at $\theta^*=90^\circ$ on the Inside Edge of the Ring (lbs/in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.035</td>
<td>0.72</td>
<td>573</td>
<td>520</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>0.61</td>
<td>1286</td>
<td>1209</td>
<td>433</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>0.48</td>
<td>2252</td>
<td>2691</td>
<td>771</td>
</tr>
<tr>
<td>0.50</td>
<td>0.028</td>
<td>0.89</td>
<td>130</td>
<td>154</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>0.035</td>
<td>0.86</td>
<td>211</td>
<td>243</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>0.80</td>
<td>494</td>
<td>530</td>
<td>241</td>
</tr>
<tr>
<td></td>
<td>0.058</td>
<td>0.77</td>
<td>644</td>
<td>686</td>
<td>303</td>
</tr>
<tr>
<td></td>
<td>0.065</td>
<td>0.74</td>
<td>944</td>
<td>956</td>
<td>404</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0.50</td>
<td>3715</td>
<td>5482</td>
<td>1567</td>
</tr>
<tr>
<td>0.75</td>
<td>0.035</td>
<td>0.91</td>
<td>136</td>
<td>153</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>0.083</td>
<td>0.78</td>
<td>1063</td>
<td>1106</td>
<td>484</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0.67</td>
<td>2393</td>
<td>2646</td>
<td>1011</td>
</tr>
</tbody>
</table>
Figure A.4. Diametric actual vs. predicted yield loads. The predicted values are for the outside edge of the ring at $\theta^* = 0^\circ$.

The point at which the predicted yield load curve, for the point located at the outside edge of a ring at $\theta^* = 0$, departs from the actual data is not consistent across the different diameters. This indicates that in rings with thick walls, outside diameter influences the yield mechanism beyond what is accounted for in the Ri/Ro ratio.

Conclusion

In diametrically loaded rings, predicted yield loads for a point located on the outside edge of a ring at $\theta^* = 0^\circ$ can be used to predict ring yield loads with good accuracy in thin walled rings. As the wall thickness increases, the mechanism controlling tube yield changes and the curve of the yield load for the outside edge of the ring $\theta^* = 0^\circ$ departs from actual yield loads. Therefore,
predicted yield loads for a point located on the outside edge of a ring at $\theta^*=0^\circ$ cannot be used to predict ring yield in thick walled rings.

In Chapter 3, it was shown that plane stress and strain assumptions are not valid in monotonically loaded lap-joints where one-inch thick LSL components are connected with hollow fasteners. Because of multi-axial stresses present in the hollow fasteners connecting these configurations of lap-joints, hollow fasteners in these joints cannot be modeled as two-dimensional, diametrically loaded rings.

References


MATLAB Programs

Program 1. Stress versus expansion terms, inside edge at $\theta^*=90^\circ$.

clear all
maxExpansionTerms=100;
Ro=0.250;
Ri=0.222;
E=10000000;
P=130;
Theta=90;
ThetaRad= (pi/180)*Theta;
Alpha=Ri/Ro;
Mo=2/(1-Alpha^2);
No=(2*Alpha)/(1-Alpha^2);
StressTerm1=-Mo*(P/(pi*Ro));
StressTerm2=(P/(pi*Ro));
DisplacementTerm1=-No*(P/(pi*E));
DisplacementTerm2=P/(pi*E);
TermStressStrainArray=zeros(maxExpansionTerms,3);
count=0;
for u=1:maxExpansionTerms
      count=count+1;
      TermStressStrainArray(u,1)=u;
      k=u;
n=zeros(1,k);
q=zeros(1,k);
for g=1:k
        n(1,g)=2*g;
        q(1,g)=(-1)^g;
        r=-1*q;
end
M=zeros(1,k);
N=zeros(1,k);
Q=zeros(1,k);
for i=1:k
        Q(1,i)=(1-(Alpha^(2*n(1,i))))^2-((n(1,i)^2)^2)*((Alpha^(2*n(1,i)-2)))*((1-
                        Alpha^2)^2));
        M(1,i)=(4*n(1,i)*(Alpha^2)*n(1,i))/Q(1,i));
        N(1,i)=((4*n(1,i)*(Alpha^2)*(1+Alpha^2))/(n(1,i)^2-1))+(1+Alpha^2)/(1-
                        Alpha^2)+(1+Alpha^2)/(1-
        ExpansionArray=zeros(k,1);
ExpansionArray2=zeros(k,1);
for h=1:k
        ExpansionArray(h,1)=(q(1,h)*M(1,h))*cos(n(1,h)*ThetaRad);
        ExpansionArray2(h,1)=(r(1,h)*N(1,h))*cos(n(1,h)*ThetaRad);
end
Stress=StressTerm1+(StressTerm2*(sum(ExpansionArray(:,1))));
TermStressStrainArray(u,2)=Stress;
Displacement=DisplacementTerm1+(DisplacementTerm2*(sum(ExpansionArray2(:,
1))));
TermStressStrainArray(u,3)=Displacement;
end
subplot(2,1,1); plot(TermStressStrainArray(:,1),TermStressStrainArray(:,2))
title('Stress vs the Number of Terms in the Series Expansion')
xlabel('Number of Terms in the Series Expansion')
ylabel(['Stress, P=',num2str(P)])
subplot(2,1,2); plot(TermStressStrainArray(:,1),TermStressStrainArray(:,3))
title('Displacement vs the Number of Terms in the Series Expansion')
xlabel('Number of Terms in the Series Expansion')
ylabel(['Strain, P=',num2str(P)])
Program 2. Stress versus expansion terms, outside edge at $\theta^* = 0^\circ$.

clear all
maxExpansionTerms=100;
Ro=0.250;
Ri=0.222;
P=130;
Theta=0;
ThetaRad=(pi/180)*Theta;
Alpha=Ri/Ro;
MoPrime=(2*Alpha^2)/(1-Alpha^2);
StressTerm1=-MoPrime*(P/(pi*Ro));
StressTerm2=(P/(pi*Ro));
TermStressStrainArray=zeros(maxExpansionTerms,2);
count=0;
for u=1:maxExpansionTerms
    count=count+1;
    TermStressStrainArray(u,1)=u;
    k=u;
    n=zeros(1,k);
    q=zeros(1,k);
    for g=1:k
        n(1,g)=2*g;
        q(1,g)=((-1)^g;
        r=-1*q;
    end
    Mprime=zeros(1,k);
    Q=zeros(1,k);
    for i=1:k
        Q(1,i)=(1-(Alpha^(2*n(1,i)))^2-((n(1,i))^2)*((Alpha^(2*n(1,i)-2))*((1-Alpha^2)^2)));
        Mprime(1,i)=((4*(1-Alpha^2)^2)/(Alpha^2))*(((n(1,i))^2)*(Alpha^(2*n(1,i))))/Q(1,i));
    end
    ExpansionArray=zeros(k,1);
    for h=1:k
        ExpansionArray(h,1)=(r(1,h)*Mprime(1,h))*cos(n(1,h)*ThetaRad);
    end
    Stress=StressTerm1+(StressTerm2*(sum(ExpansionArray(:,1))));
    TermStressStrainArray(u,2)=Stress;
end
plot(TermStressStrainArray(:,1),TermStressStrainArray(:,2))
title('Stress vs the Number of Terms in the Series Expansion')
xlabel('Number of Terms in the Series Expansion')
ylabel(['Stress, P=',num2str(P)])

Program 3. Calculation of yield load on the inside edge at $\theta^* = 0^\circ$. 
clear all
DowelDiameter=0.495825;
WallThickness=0.057662;
t=1;
RingFail=40000;
MaxLoad=10000;
Ro=DowelDiameter/2;
Theta=90;
ThetaRad=(pi/180)*Theta;
increment=1;
ExpansionTerms=25;
count=0;
Ri=Ro-WallThickness;
Alpha=Ri/Ro;
Mo=2/(1-Alpha^2);
No=(2*Alpha)/(1-Alpha^2);
n=zeros(1,ExpansionTerms);
q=zeros(1,ExpansionTerms);
for g=1:ExpansionTerms
    n(1,g)=2*g;
    q(1,g)=(-1)^g;
    r=-1*q;
end
M=zeros(1,ExpansionTerms);
N=zeros(1,ExpansionTerms);
Q=zeros(1,ExpansionTerms);
for i=1:ExpansionTerms
    Q(1,i)=(1-(Alpha^((2*n(1,i))))-(n(1,i))^2)*((Alpha^((2*n(1,i)-2)))*(1-Alpha^2)))/Q(1,i));
    M(1,i)=((4*n(1,i)*Alpha^((n(1,i)-1)))+(n(1,i)^2-1))*((n(1,i)*1-Alpha^2)*(1+Alpha^2)*(1-Alpha^((2*n(1,i)))+1+Alpha^2)*(1-Alpha^((2*n(1,i)))+1+Alpha^2))/Q(1,i));
end
ExpansionArray=zeros(ExpansionTerms,1);
ExpansionArray2=zeros(ExpansionTerms,1);
for h=1:ExpansionTerms
    ExpansionArray(h,1)=(q(1,h)*M(h,1))*cos(n(1,h)*ThetaRad);
end
for P=increment:increment:MaxLoad
    p=P/t;
    StressTerm1=-Mo*(p/(pi*Ro));
    StressTerm2=(p/(pi*Ro));
    Stress=StressTerm1+(StressTerm2*(sum(ExpansionArray(:,1))));
    if(Stress>=RingFail)
        'Ring Failure'
        Stress
        P
    end
end
Program 4. Calculation of yield load on the outside edge at $\theta^* = 90^\circ$.

```
clear all
DowelDiameter=0.495825;
WallThickness=0.057662;
t=1;
RingFail=40000;
MaxLoad=90000;
Ro=DowelDiameter/2;
Theta=0;
ThetaRad=(pi/180)*Theta;
increment=1;
ExpansionTerms=25;
count=0;
Ri=Ro-WallThickness; % this is the inside radius of the tube
Alpha=Ri/Ro;
MoPrime=(2*Alpha^2)/(1-Alpha^2);
n=zeros(1,ExpansionTerms);
q=zeros(1,ExpansionTerms);
for g=1:ExpansionTerms
    n(1,g)=2*g;
    q(1,g)=(-1)^g;
    r=-1*q;
end
Mprime=zeros(1,ExpansionTerms);
Q=zeros(1,ExpansionTerms);
for i=1:ExpansionTerms
    Q(1,i)=(1-(Alpha^((2*n(1,i))))^2-((n(1,i))^2)*((Alpha^((2*n(1,i)-2))*((1-Alpha^2)^2))));
    Mprime(1,i)=((4*(1-Alpha^2)^2)/(Alpha^2))*(((n(1,i)^2)*(Alpha^((2*n(1,i)))))/Q(1,i));
end
ExpansionArray=zeros(ExpansionTerms,1);
for h=1:ExpansionTerms
    ExpansionArray(h,1)=(r(1,h)*Mprime(1,h))*cos(n(1,h)*ThetaRad);
end
for P=increment:increment:MaxLoad
    p=P/t;
    StressTerm1=-MoPrime*(p/(pi*Ro));
    StressTerm2=(p/(pi*Ro));
    Stress=StressTerm1+(StressTerm2*(sum(ExpansionArray(:,1))));
    if(Stress>=RingFail)
        break
    end
end
```
'Ring Failure'
Stress
P
p
break
end
end
Appendix B. Modeling of LSL Bearing Behavior

Introduction

Test results in Chapter 3 show that the yield behavior of monotonically loaded lap-joints connected with hollow fasteners can be characterized along a continuum where extremes in behavior are defined by wall thickness of the hollow fasteners. In LSL joints connected with solid dowels, joint yield occurred through deformation of the LSL. In LSL joints connected with hollow tubes with very thin walls, joint yield occurred primarily through buckling and deformation within the hollow fastener. Between behaviors of the extremes, joint yield occurred through varying degrees of fastener wall buckling and LSL deformation. Defining the point at which joint yield is predominantly due to tube buckling is necessary to enable designing joints that yield primarily through tube buckling.

The process of selecting components to construct a lap-joint such that yield occurs primarily through buckling of the hollow fastener can be split into two parts: determining a load that the bearing substrates can withstand without exceeding a predetermined level of deformation, and determining a tube diameter and wall thickness combination that will yield at or before a defined load is reached. This appendix discusses an attempt to employ a mechanics of materials based modeling approach to predict failure in the bearing components loaded under bolts.

Model Development

Yadama (2010) developed a mechanics of materials based approach to calculate vertical, horizontal, and shear stress in a bearing member resulting from a dowel bearing load. The approach begins with applying contact stress theory on two cylinders in contact. The contact
between a dowel and the bearing is assumed to be analogous to two cylinders in contact as shown in Figure B.1. The dowel is assumed to be solid, the deflections are assumed to be small, and the materials in contact are assumed to be isotropic. The half-width of the contact area, $a$, is calculated with the formula (Budynas, 1977):

$$a = 2\sqrt{\frac{PR_b(-R_c)(1-v_c^2)E_b + (1-v_b^2)E_c}{\pi E_b E_c (R_b - R_c)}}$$

Eqn. B.1

Where,

$a$=half-width of the contact zone (see Figure 3)

$P$=applied load

$R_b$=radius of the dowel

$R_c$=radius of the dowel hole

$v_b$=Poisson’s ratio of the dowel material

$v_c$=Poisson’s ratio of the bearing material

$E_b$=Modulus of elasticity of the dowel material

$E_c$=Modulus of elasticity of the bearing material

$t$=thickness of the bearing material specimen
Once the half-width of the contact area has been calculated, then $\theta_1$, $\theta_2$, and $\beta$, as defined in Figure B.2, can be calculated. Yadama uses angles $\theta_1$, $\theta_2$, and $\beta$, to calculate radial stress beneath the dowel using Airy’s stress function for a semi-infinite plate with a distributed normal load. In polar coordinates, Airy’s stress function is defined as a function of $r$ and $\theta$ and is written (Budynas, 1977):\

$$
\nabla^4 = \left( \frac{\partial^2}{\partial r^2} + \frac{1}{r^2} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} \right)^2 \phi = 0
$$

Eqn. B.2
The stresses are given by

\[\sigma_r = \frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \phi}{\partial \theta^2}\]  
Eqn. B.3

\[\sigma_\theta = \frac{\partial^2 \phi}{\partial r^2}\]  
Eqn. B.4

\[\tau_{r\theta} = \frac{1}{r^2} \frac{\partial \phi}{\partial \theta} - \frac{1}{r} \frac{\partial^2 \phi}{\partial r \partial \theta}\]  
Eqn. B.5

The following stress function was then used to solve for the stresses

\[\phi = C_1 \theta + C_2 r^2 \theta + C_3 r \theta \sin \theta + C_4 r \theta \cos \theta\]  
Eqn. B.6

Where \(C_1, C_2, C_3,\) and \(C_4\) are constants. For equilibrium, the stresses are:

\[\sigma_r = 2C_2 \theta + \frac{2}{r} \left( C_3 \cos \theta - C_4 \sin \theta \right)\]  
Eqn. B.7

\[\sigma_\theta = 2C_2 \theta\]  
Eqn. B.8

\[\tau_{r\theta} = \frac{C_1}{r^2} - C_2\]  
Eqn. B.9

Through consideration of symmetry and through application of the boundary conditions, it can be shown that \(C_1 = C_2 = C_3 = 0\) and:

\[C_4 = \frac{2P}{t \left( 2\theta_2 - 2\theta_1 - \sin 2\theta_2 + \sin 2\theta_1 \right)}\]  
Eqn. B.10

Radial stress is then given by:

\[\sigma_r = -\frac{2C_4}{r} \sin \theta\]  
Eqn. B.12
The stresses beneath the bolt can be resolved in an x-y coordinate system by (Dally and Riley, 1991):

\[
\sigma_x = \frac{2C_4}{R_b} \left( -\frac{1}{3} \cos^3(\beta) + \frac{1}{3} \right) ~ \text{Eqn. B.13}
\]

\[
\sigma_y = \sigma_x \sin^2 \theta \quad \text{Eqn. B.14}
\]

\[
\tau_{xy} = \sigma_x \sin \theta \cos \theta \quad \text{Eqn. B.15}
\]

Once the individual stresses were calculated, the Tsai-Wu failure criterion was applied to determine failure loads. The Tsai-Wu criterion is written (Tsai and Wu, 1971):

\[
F_1 \sigma_1 + F_2 \sigma_2 + F_3 \sigma_3 + F_4 \sigma_4 + F_5 \sigma_5 + F_6 \sigma_6 + F_{11} \sigma_{11}^2 + F_{22} \sigma_{22}^2 + F_{33} \sigma_{33}^2
+ F_{44} \sigma_{44}^2 + F_{55} \sigma_{55}^2 + F_{66} \sigma_{66}^2 + 2F_{12} \sigma_1 \sigma_2 + 2F_{13} \sigma_1 \sigma_3 + 2F_{23} \sigma_2 \sigma_3 \leq 1 \quad \text{Eqn. B.16}
\]

For orthotropic materials under plane stress, Equation B.16 simplifies to (Wu and Stachurski, 1984):

\[
F_1 \sigma_1 + F_2 \sigma_2 + F_{11} \sigma_{11}^2 + F_{22} \sigma_{22}^2 + F_{66} \sigma_{66}^2 + 2F_{12} \sigma_1 \sigma_2 = 1 \quad \text{Eqn. B.17}
\]

Where \( F_1, F_2, F_{11}, \) and \( F_{66} \) are related to the uni-axial tensile and compressive strengths in the 1 and 2 directions, \( T_1, C_1, T_2, C_2, \) and the shear strength \( S_{12} \) by:

\[
F_1 = \frac{1}{T_1} - \frac{1}{C_1} \quad \text{Eqn. B.19}
\]

\[
F_2 = \frac{1}{T_2} - \frac{1}{C_2} \quad \text{Eqn. B.20}
\]

\[
F_{11} = \frac{1}{T_1C_1} \quad \text{Eqn. B.21}
\]
\[ F_{22} = \frac{1}{T_2 C_2} \quad \text{Eqn. B.22} \]

\[ F_{66} = \frac{1}{S_{12}^2} \quad \text{Eqn. B.23} \]

Because determining the interaction term \( F_{12} \) is experimentally difficult, two approximations of \( F_{12} \) were used in addition to setting \( F_{12} \) equal to zero. Wu and Stachurski (1984) proposed an approximation for \( F_{12} \) given by:

\[ F_{12} = -\frac{1}{T_1 C_1 + T_2 C_2} \quad \text{Eqn. B.23} \]

Tsai and Hahn (1980) proposed an approximation for \( F_{12} \) given by:

\[ F_{12} = -\frac{1}{2 \sqrt{\frac{1}{T_1 C_1 T_2 C_2}}} \quad \text{Eqn. B.24} \]

**Materials & Methods**

The LSL used in testing was that which was described in Chapter 3. Dowel bearing testing was performed as described in Chapter 4. Additional mechanical tests of the LSL were conducted on a screw driven universal testing machine equipped with a computerized data acquisition system. Shear tests in both the parallel and perpendicular orientations of the LSL were completed in accordance with ASTM D 143-94. The crosshead speed used in shear testing was 0.024 in./min. The deformation rate used for tension and compression testing was 0.01 in./in./min. Deformation rate was used to determine the crosshead rate of travel by dividing the length of the test specimen by the speed of the crosshead and equating that with the deformation
rate. Twelve tests were performed for both tension and compression in both parallel and perpendicular orientations of the LSL. The modulus of elasticity (MOE) and ultimate strength for both the parallel and perpendicular orientations of the LSL were determined.

All tension tests employed a two-inch extensometer placed within the gauge length of the test specimens. Tension and compression testing were completed in accordance with ASTM D5456-09 and D4761-05. Tension specimen sizes deviated from the standard. Tension parallel specimens were 28 x 1.25 x 3 inches tapered to 2 inches for a gauge length of 14 inches. The specimen size allowed for more than twice the longest strand length between the grips. Tension perpendicular specimens were 14 x 1.25 x 3 inches tapered to 2 inches for a gauge length of 6.25 inches.

Compression tests employed a two-inch extensometer. The bottom plate of the test fixture was fixed and the top plate rotated on a ball joint. All compression specimens were 1.25 x 1.25 x 5 inches. The width and thickness of the specimens were dictated by the nominal thickness of the LSL.

The values for MOE, ultimate strength, and shear strength used as inputs in the model were determined through mechanical testing of the LSL. Poisson’s ratio was assumed to be 0.33. The sensitivity of the model to Poisson’s ratio was evaluated by graphing the half-width of the contact area as well as stress values by Poisson’s ratio. The graphs in Figure B.3 show how the calculations of the half-width of the contact area and the decomposed stresses change with varying Poisson’s ratio. While the calculations do vary with changing Poisson’s ratio, the overall magnitude of the changes between 0.3 and 0.4 represent small percentage changes in the respective calculations.
Due to the difficulty in experimentally determining the interaction term $F_{12}$ in the Tsai-Wu failure criteria, three approximations for the interaction term $F_{12}$ in the Tsai-Wu failure criteria were used. The effect of the different values of $F_{12}$ on the failure envelope is illustrated in Figure B.5. While the $F_{12}$ term significantly affects the shape of the failure envelope, changing the shape of the failure envelope had no impact on predicted failure loads as the failure loads were projected near the principal axes resulting in near uni-axial stress states.
Figure B.4. Tsai-Wu failure envelope for three values of the interaction term $F_{12}$. The small circles represent failure loads predicted by the model.
Results and Discussion

Table B.1 lists the mechanical properties of the LSL determined through physical testing. The values in Table B.1 were used as inputs into the model to predict failure loads for the LSL.

Table B.1. LSL physical properties.

<table>
<thead>
<tr>
<th>Load Configuration</th>
<th>Orientation</th>
<th>Property</th>
<th>Average Value (psi)</th>
<th>Coefficient of Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>Parallel</td>
<td>Modulus of Elasticity</td>
<td>1304000</td>
<td>10.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ultimate Stress</td>
<td>4690</td>
<td>13.00</td>
</tr>
<tr>
<td></td>
<td>Perpendicular</td>
<td>Modulus of Elasticity</td>
<td>237000</td>
<td>21.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ultimate Stress</td>
<td>1104</td>
<td>14.50</td>
</tr>
<tr>
<td>Compression</td>
<td>Parallel</td>
<td>Modulus of Elasticity</td>
<td>1337000</td>
<td>18.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ultimate Stress</td>
<td>4930</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>Perpendicular</td>
<td>Modulus of Elasticity</td>
<td>200000</td>
<td>31.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ultimate Stress</td>
<td>1410</td>
<td>13.20</td>
</tr>
<tr>
<td>Shear</td>
<td>Parallel</td>
<td>Ultimate Stress</td>
<td>717</td>
<td>17.03</td>
</tr>
<tr>
<td></td>
<td>Perpendicular</td>
<td>Ultimate Stress</td>
<td>536</td>
<td>16.99</td>
</tr>
</tbody>
</table>

Predicted failure loads for the LSL are listed in Table B.2. Dowel bearing failure loads determined through the five-percent offset method specified in ASTM 5764-97a are listed as the actual failure loads in Table B.2. The predicted failure loads do not approximate the actual yield loads. The large disparity between the predicted and actual failure loads suggest that the model fails to represent the physical interactions in the LSL under a dowel.
Table B.2. Actual versus predicted yield loads in substrates below loaded fasteners.

<table>
<thead>
<tr>
<th>LSL Orientation</th>
<th>Dowel Diameter (in.)</th>
<th>Actual Yield Load as Determined by the 5% offset dowel bearing load (lbs)</th>
<th>Predicted Yield Load (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>0.75</td>
<td>5160</td>
<td>305</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>3508</td>
<td>166</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>2077</td>
<td>55</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>0.75</td>
<td>4259</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>3007</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>1616</td>
<td>35</td>
</tr>
</tbody>
</table>

The poor physical representation of the model is due, in part, to its lack of accounting for transverse stress components. The model does not allow for the development of transverse stress resulting from compression directly below the bolt. In wood loaded in compression, transverse stresses develop as tension parallel to the applied load (Markwardt and Wilson, 1935). The lack of allowance for transverse stress development resulting from compression loads prevent the model from mimicking the behavior in LSL and causes the model to be extremely sensitive to hole clearance around the dowel.

In mathematical modeling, the diameter of the pilot hole drilled to accept the dowels was fixed at 0.03125 inches greater than the dowel it was intended to accept in order to match the testing conditions. Even though the clearance of the pilot hole was fixed, the sensitivity of the stress calculations to the pilot hole diameter was evaluated. The graphs in Figure B.4 are for stress calculations with a 0.5-inch dowel, a fixed load, and variable dowel clearance. Figure B.4 illustrates that the calculation for stress parallel to the load (Y-direction stress) is extremely sensitive to the dowel hole radius for values close to the diameter of the dowel. This effect results from increasing the clearance around the bolt leading to decreasing the amount of lateral...
contact around the bolt thus reducing the pathway for stress transfer in the X-direction which leaves the load to be resisted primarily in the Y-direction.

Figure B.5. Effect of dowel hole radius on stress calculations and on the calculation of the half-width of the contact area. Dowel diameter = 0.5 inches.

Another contributing factor to model inaccuracy may be due to the method used in the determination of the LSL compression stiffness. Several researchers have noted a specimen size effect in the determination of compression MOE in cellular materials. They noted that MOE has been observed to increase with increasing test specimen height (Linde et al, 1992; Onck et al, 2001; Andrews et al, 2001). The dependence of compression MOE upon test specimen size was
attributed to surface roughness relative to specimen size. Rough surfaces are inherent to cellular materials as cutting of cellular materials will expose open cells to the surface. When these materials are loaded in compression, non-uniform stress fields develop in the areas in contact and those areas deform. The deformation in these areas happens at apparent low stress levels when stress in the specimen is calculated by dividing load by the entire cross-section of the test specimen. Additionally, deformation in the rough areas increases the overall deformation, which results in lower MOE if strain is defined as the change in specimen length divided by the specimen height.

In this work, compression MOE was determined through testing which incorporated an extensometer and thus the influence of surface roughness was eliminated from the model input. However, in dowel bearing loading, some deformation occurs at the interface between the dowel and the LSL and thus surface roughness and the associated deformation impacts the test results. Because surface roughness effects were eliminated in the materials characterization, the compression MOE used as a model input was likely too high compared to the compression response of the LSL under the bolt in dowel bearing testing. To gauge the effect that the magnitude of the compression MOE has on the failure load predictions, the compression MOE value was reduced to three percent of the value measured and the predictions were recalculated. The predicted failure loads roughly doubled from the original values, but were still well below the observed yield loads. It is likely that the compression MOE used as a model input was too high to match the physical reality, however it appears that difference did not account for the majority of the discrepancy between predicted and actual failure loads.

An additional mismatch between the model and the actual test results lies in the assumption regarding the failure mode. An implicit assumption of the contact stress model, as it
was applied here, was that brittle failure was assumed to occur when the predicted failure load was reached. The failure mode observed in dowel bearing testing was ductile and the LSL continued to resist increasing load after yield. It is likely that plastic deformation in the LSL allowed for greater load resistance than expected with the brittle failure assumption.

**Conclusion**

The predicted failure loads do not accurately approximate the actual yield loads. The large disparity between the predicted and actual failure loads suggest that the model fails to represent the physical interactions in the LSL under a dowel. A portion of the poor physical representation of the model lies in its lack of accounting for transverse stress components. Additionally, the model assumed brittle failure behavior; however, ductile failure behavior was observed in the validation testing. Another discrepancy in the model was that it employed a compression MOE value that likely overestimated the stiffness of the actual material response to loading in the dowel bearing testing.

**References**


Additional graphs showing the effect of dowel hole radius on stress calculations

Figure B.6. Effect of dowel hole radius on stress calculations and on the calculation of the half-width of the contact area. Dowel diameter = 0.25 inches.
**Figure B.7.** Effect of dowel hole radius on stress calculations and on the calculation of the half-width of the contact area. Dowel diameter = 0.75 inches.

### MATLAB Programs

Program 1. Sensitivity of the stress calculations to Poisson’s ratio.

```matlab
clear all
P=550;
Ro=0.2515;
Rc=0.28125;
t=1;
E=10000000;
Ec=1300000;
vb=0.334;
PoissonLow=0.2;
PoissonHigh=0.5;
PoissonIncrement=0.001;
```
DataArray=zeros(((PoissonHigh-PoissonLow)/PoissonIncrement),5);
Theta=90;
count=0;
for vc=PoissonLow:PoissonIncrement:PoissonHigh
    count=count+1;
    ThetaRad=(pi/180)*Theta;
    a=2*((P*Ro*(-Rc)*(((1-vc^2)*E)+((1-vb^2)*Ec)))/(pi*t*E*Ec*(Ro-Rc)))^0.5;
    Beta=asin(a/Ro);
    Theta1=(pi/2)-Beta;
    Theta2=(pi/2)+Beta;
    C4=(2*P)/(t*((2*Theta2)-(2*Theta1)-(sin(2*Theta2))+sin(2*Theta1))));
    Radial=-1*((2*C4)/Ro)*sin(ThetaRad);
    SigmaX=-2*C4/Ro;
    SigmaY2=Radial*sin(ThetaRad)^2;
    TauXY=Radial*sin(Theta1)*cos(Theta1);
    DataArray(count,1)=vc;
    DataArray(count,2)=a;
    DataArray(count,3)=SigmaX;
    DataArray(count,4)=SigmaY;
    DataArray(count,5)=TauXY;
end
subplot(2,2,1); plot(DataArray(:,1),abs(DataArray(:,2)))
title('Poisson Ratio vs Half Width of Contact Area')
xlabel('Poissons Ratio')
ylabel('a, Half Width of Contact Area')
subplot(2,2,2); plot(DataArray(:,1),abs(DataArray(:,3)))
title('Poissons Ratio vs X-Direction Stress')
xlabel('Poissons Ratio')
ylabel('X-Direction Stress (psi)')
subplot(2,2,3); plot(DataArray(:,1),abs(DataArray(:,4)))
title('Poissons Ratio vs SigmaY')
xlabel('Poissons Ratio')
ylabel('Y-Direction Stress')
subplot(2,2,4); plot(DataArray(:,1),abs(DataArray(:,5)))
title('Poissons Ratio vs Shear Stress')
xlabel('Poissons Ratio')
ylabel('Shear Stress (psi)')

clear all
P=133;
Ro=0.2515;
t=1;
E=10000000;
Ec=1300000;
vb=0.334;
vC=0.33;
Theta=90;
ThetaRad=(pi/180)*Theta;
increment=0.0001;
DataArray=zeros(((round((Ro+1)/(Ro+0.005)))+1),4);
count=0
for Rc=(Ro+0.005):increment:(Ro+1)
    count=count+1;
    a=2*(((P*Ro*(-Rc))^(((1-vC^2)*E)+((1-vb^2)*Ec)))/(pi*t*E*Ec*(Ro-Rc)))^0.5;
    Beta=asin(a/Ro);
    Theta1=(pi/2)-Beta;
    Theta2=(pi/2)+Beta;
    C4=(2*P)/(t*((2*Theta2)-(2*Theta1)-(sin(2*Theta2))+(sin(2*Theta1))));
    Radial=1*((2*C4)/Ro)*sin(ThetaRad);
    SigmaX=(-2*C4)/Ro;
    SigmaY2=Radial*sin(ThetaRad)^2;
    TauXY=Radial*sin(Theta1)*cos(Theta1);
    DataArray(count,1)=Rc;
    DataArray(count,2)=SigmaX;
    DataArray(count,3)=SigmaY;
    DataArray(count,4)=TauXY;
end
Maximums=abs(max(DataArray));
'Column 1 = Rc, Column 2 = SigmaX, Column 3 = SigmaY, Column 4 = TauXY'
DataArray
subplot(2,2,1); plot(DataArray(:,1),abs(DataArray(:,2)))
title('X Direction Stress vs Dowel Hole Radius')
%gtext(['Dowel Outside Radius=',num2str(Ro)])
%text(Maximums(1,1)*0.7, Maximums(1,2), ['Dowel Outside Radius=',num2str(Ro)])
xlabel('Radius of Dowel Hole')
ylabel('X-Direction Stress (psi)')
subplot(2,2,2); plot(DataArray(:,1),abs(DataArray(:,3)))
title('Y Direction Stress vs Dowel Hole Radius')
%gtext(['Dowel Outside Radius=',num2str(Ro)])
xlabel('Radius of Dowel Hole')
ylabel('Y-Direction Stress (psi)')
subplot(2,2,3); plot(DataArray(:,1),abs(DataArray(:,4)))
title('Shear Stress vs Dowel Hole Radius')
gtext(['Dowel Outside Radius=',num2str(Ro)])
xlabel('Radius of Dowel Hole')
ylabel('Shear Stress (psi)')

subplot(2,2,4);
plot(DataArray(:,1),abs(DataArray(:,2)),DataArray(:,1),abs(DataArray(:,3)),DataArray(:,1),abs(DataArray(:,4)))
legend('X-Direction Stress','Y-Direction Stress', 'Shear Stress')
title('Stress vs Dowel Hole Radius')
xlabel('Radius of Dowel Hole')
ylabel('Shear Stress (psi)')

Program 3. Failure load prediction in bearing materials

clear all
Ro=0.371;
Rc=0.4045;
t=1.25325;%average bearing substrate thickness for the 0.75" dowel bearing tests (parallel)
E=10000000;
Ec=1336950
vb=0.334;
vc=0.33;
Theta=90;
ThetaRad=(pi/180)*Theta;
loadincrement=1;
loadlimit=10000;
t1=4689;
c1=4926;
t2=1104;
c2=1413;
es=717;
F1=(1/t1)-(1/c1);
F11=1/(t1*c1);
F2=(1/t2)-(1/c2);
F22=1/(t2*c2);
F66=1/(es^2);
F12a=-1/((t1*c1)+(t2*c2));
F12b=(-1/2)*((F11*F22)^0.5);
F120=0;
count=0;
for P=loadincrement:loadincrement:loadlimit%load
    count=count+1;
a=2*(((P*Ro*(-Rc))*(((1-vc^2)*E)+((1-vb^2)*Ec)))/(pi*t*Ec*(Ro-Rc))^0.5);
Beta = \arcsin\left(\frac{a}{Ro}\right);
Theta_1 = \frac{\pi}{2} - Beta;
Theta_2 = \frac{\pi}{2} + Beta;
C_4 = \frac{2P}{t\left(2\Theta_2 - 2\Theta_1 - \sin(2\Theta_2) + \sin(2\Theta_1)\right)};
Radial = -1 \left(\frac{2C_4}{Ro}\right) \sin(\text{ThetaRad})
Sigma_2 = \left(-\frac{2C_4}{Ro}\right) \left(-\frac{1}{3}\cos(Beta)^3 + \frac{1}{3}\right) - 1;
Sigma_1 = \left(-\frac{2C_4}{Ro}\right);
Sigma_1 \text{ Check} = \text{Radial} \sin(\text{ThetaRad})^2;
Tau_{XY} = \text{Radial} \sin(\text{Theta}1) \cos(\text{Theta}1);
TWo = F_1 \Sigma_1 + F_2 \Sigma_2 + F_{11} \Sigma_1^2 + 2F_{12} \Sigma_1 \Sigma_2 + F_{22} \Sigma_2^2 + F_{66} \tau_{XY}^2;
if (TWo >= 1)
    break
end

P
Sigma_1
Sigma_2
Tau_{XY}
TWo