EXAMINING THE SHEAR STRENGTH OF THE GLUE LINES IN GLUED LAMINATED TIMBER

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April 24th, 2017

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An undergraduate thesis submitted in partial fulfillment
of the requirements for the degree of
Honours Bachelor of Science in Forestry

Faculty of Natural Resources Management

Lakehead University

Thunder Bay, ON

April 25th, 2016

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A CAUTION TO THE READER

ABSTARCT

Gleeson, R. J. 2017. Examining the shear strength of the glue lines in glued laminated timber. 63 pp.

Keywords: building codes, carbon, concrete, construction, conventional, engineered, glue line, glulam, Nordic, peak load, *Picea mariana*, wood products, steel, variability.

With a soaring global population and continuous depletion of resources, wood and engineered wood products will change the way we carry out conventional construction. Conventional building materials such as concrete and steel have temporarily controlled the construction market but wood is making a serious comeback. Evolving building codes is facilitating this shift as they are allowing larger timber structure to be built. There are numerous benefits in using wood as a building material and historically wood has been used for just everything as it is still today. At the forefront of this shift are engineered wood products.

This study focuses on the shear strength of the glue lines within glulam bolts constructed of *Picea mariana* Lamb. pieces from the Quebec based glulam facility, Nordic. Roughly twenty replicates were obtained from five glulam bolts for a grand total of ninety-seven samples tested for shear strength on the glue line. It was hypothesized that there would be no difference in shear strength between the five bolts. This hypothesis was rejected as the results showed that average peak load for the tests was 21,354.59 N and the presence of significant differences in average peak load between bolts. These results are congruent the published value for shear strength (21,920 N) in clear black spruce, which means that the glue lines did not have an affect on shear strength. The significant differences between bolts may be explained by the inherent variability of wood.

ACKNOWLEDGEMENTS

I would like to thank Dr. M. Leitch for supervising my undergraduate thesis and also allowing me to conduct my analyses in is Lakehead University Wood Science Testing Facility (LUWSTF). Thank you to Dr. S. Shahi for signing as my second reader and assisting me in my statistical analysis. I would also like to than Dr. S. Salem for supplying the glulam beams used in my study and the staff of the engineering testing facility for allowing me to use their equipment. Finally, I would like to thank my colleagues Vanessa Green and Cole Wear for helping me prepare my samples and provide additional direction for my thesis.

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1 INTRODUCTION

As the population of the world continues to grow it is inevitable that we will eventually deplete our finite non-renewable resources in efforts to support such a vast number of humans. Knowing this, natural resources are more important now than they have ever been. The ability to naturally grow a product is a paramount advantage that we as a society must adopt. With issues surrounding climate change, green house gas emissions, burning fossil fuels…etc., using renewable resources is what will ultimately shape our future and ensure social, economic and environmental aspects are all satisfied.

An area where the shift toward the usage of renewable resources is prevalent is the construction industry. The use of conventional construction methods that are heavily reliant on steel and concrete is beginning to decline. The interest in wood structures in Canada is augmented by recent changes in building codes that allow for taller/larger wood-based structures. Wood buildings have been rapidly gaining popularity as an alternative to these conventional materials since wood has a number of advantageous properties and is also very versatile.

The advantages of using wood as a building material are plenty. The ability to sequester carbon and mitigate greenhouse gas emissions is one of the primary benefits of using wood (Buchanan 2007). Wood also has the ability to withstand fire via innate defense mechanisms and it has favorable mechanical properties that make it very strong and durable (USDA 2010). In addition, wood has very good insulator properties compared to concrete and steel (Atlantic WoodWORKS 2016.). It has been proven that it is both cheaper and more efficient to build with wood (Atlantic WoodWORKS 2016.) and wood is just nicer to look at and has the ability to positively impact mental health (Fell 2010 and Burnard and Kutnar 2015). Lastly wood is a renewable material, unlike other conventional building materials.

At the forefront of this shift away from conventional materials you will find engineered wood products (EWPs). By definition, engineered wood products are materials that have been fabricated by bonding wood fibres together (Low and Burns 2013). Some of these products include: cross-laminated timber (CLT), oriented strand board (OSB), laminated veneer lumber (LVL), I joists and glued laminated timber (glulam), which is the product this thesis will be focusing on. The theory behind the birth of engineered wood products is the notion that connecting individual wood portions together will enhance the inherent properties of wood. Thus, yielding larger, stronger and more durable timber structures. So essentially, engineered wood products allows you to take average lumber and create mass timber structures that posses desirable properties. In addition, these engineering methods facilitate the production of larger pieces of timber that can span large distances (300ft.+), which is an obvious advantage over sawn wood.

For the purpose of this study, glulam will be the product I will be examining. Simply put, glulam timber results from the bonding of multiple layers of dimensional lumber with durable adhesives capable of creating mass timber structures. Following recent code changes for construction, glulam is gaining popularity and is used in a variety of applications, such as large roofing systems and buildings. There are several benefits that arise from using glulam timber: it is a renewable resource, it is aesthetically pleasing, easily manipulated (custom shapes/sizes), has an ideal strength to weight ratio, its durability and finally its resistance to fire (Buckland Timber 2012). It is clear glulam is a viable alternative to traditional building materials mentioned previously. However, manufacturers must ensure that certain standards are met to guarantee the best performance of the timber structure when put into service.

1.1 OBJECTIVES

The primary objectives of this thesis is to:

1) examine the shear strength of the glue lines within the glulam samples and determine if the results from testing meet ANSI Standard A190.1-2012, Standard for Wood Products—Structural Glued Laminated Timber and ASTM D905-08,
2) examine if the shear strength results are consistent throughout all of the samples between and within a glulam sample,
3) identify possible reasons for variation in shear property tests, and
4) observe the penetration of the glue into the wood cells using an SEM

1.2 HYPOTHESES

The hypothesis of this thesis is therefore:

The sample will meet or exceed the required standards and shear strength properties and these properties will remain consistent throughout the samples.

The null hypothesis of this thesis is therefore:

There is no significant difference in shear strength between the glulam bolts.

2 LITERATURE REVIEW

Historically wood was a primary building material, however, the market for wood had been lost to other building materials such steel and concrete. Fortunately for the timber industry, the trend toward wood as a primary building material is gaining popularity once again. With the shift toward natural and sustainable practices, wood is leading this movement. There are a number of inherent properties that wood possesses that make it such an ideal substitute for conventional materials such as steel and concrete.

2.1 ADVANTAGES OF USING WOOD

2.1.1 Carbon Sequestration and CO_2 Emission Reduction

With the growing concern about climate change in today's society forests can and will play a significant role, as they represent a large carbon sink sequestering CO_2 from the atmosphere and storing it within woody biomass throughout the life of a tree. Old growth forests especially are important in this carbon mitigation as they accumulate carbon over the entire life of a tree, which could be centuries in some cases. For example, an old growth Redwood can live for several thousand years. Luyssaert et al. (2008) and Dong et al. (2004) attempted to quantify the amount of carbon that primary forests in the Northern Hemisphere actually sequester. Luyssaert et al. (2008) concluded that these forests sequester an estimated 1.3 (+/- 0.5) gigatonnes of carbon per year. However, they do note that they expect much of this carbon will eventually move back to the atmosphere if these forests are disturbed. Dong et al. (2004) presented similar results with an estimated 0.68 (+/- 0.34) gigatonnes per year. Knowing this, we can assume that once this timber is put into commercial use it will continue to store the sequestered carbon and prevent it from being released into the atmosphere. Perez-Garcia et al. (2004) also spoke about the role of forest management in carbon cycling. Ultimately they concluded that effective forest management will lead to a reduction in atmospheric carbon by displacing more fossil fuel intensive products in housing and infrastructure.

Buchanan (2007), Börjesson and Gustavsson (2000) and Sathre (2007) documented that one of the primary advantages to using wood for buildings is that it is a sustainable practice that reduces fossil fuel energy emissions and CO_2 emissions. Buchanan (2007) explained this conclusion by analyzing wood as a building material and also provided criteria that building materials should meet. The criterion states that building materials should be: renewable, low CO_2 emissions, locally sourced if possible, create minimum waste, low energy, reusable and recyclable and non-polluting. It is no coincidence that wood satisfies all of the criteria, which solidifies its spot as an ideal building material. Börjesson and Gustavsson (2000) carried out a study to confirm the notion that wood frames do in fact produce far less emissions compared to steel and concrete. Their study concluded that the energy input for concrete was 60-80% higher compared to wood frames. Finally, Sathre (2007) studied the mechanisms by which wood product substitution can affect energy and atmospheric carbon balances. His study concluded that intensive forest management that leads to greater amounts of biomass results in a net CO_2 emissions benefit. Furthermore, he states that although intensive management uses more energy and produces more CO_2, it is more than compensated by emissions reduction due to product substitution.

2.1.2 Fire Resistance and Retardants

Beyond the benefits of carbon storage and atmospheric reduction, utilization of wood in construction has numerous advantages that are unique to its genetic structure. Wood is unlike any other material in the world due to its versatility and the ability to be easily manipulated. Contrary to common beliefs, in the presence of fire, mass timber structures are actually more durable than materials like concrete and steel, once certain temperatures are reached. Rowell and Dietenberger (2013) documented this fact using the argument that wood has a process by which the outer portion of a burnt (charred) piece of wood actually acts as a protective layer to impede the damage to the inner layers of wood. To validate their literature they used the example of the 1953 fire at a casein plant in Frankfort, New York. In this situation the metal girders softened and failed after just hours of burning, while the large wood beams remained structurally sound after several hours of burning (figure 1). Not only did the large wood beams remain they can be seen carrying the load of the steel beams, even after the fire burnt a significant amount of wood from the beam (figure 1). However, Jirouš-Rajković and Miklečić (2009) stated the fact that wood will inevitably burn to the point of failure if exposed to fire long enough.

Figure 1. A wood beam that survived the fire in the casein plant in Frankfort, New York.

Source: Rowell (2005)

Jirouš-Rajković and Miklečić (2009) discussed the development of fire retardants for wood. They stated that retardants control ignition as well as the spread of the flame along the wood surface and reduces the amount of heat released from the wood. They also noted that the application of fire retardants is important for meeting requirements needed for certain commercial uses of wood structures. Rowell (2005) also discussed fire retardants and stated that fire retardant treatments for wood can be classified into one of six classes:

1) chemicals that promote the formation of increased char at a lower temperature than untreated wood (Ex. ammonium dihydrogen orthophosphate),
2) chemicals which act as free radical traps in the flame (Ex. bromine and chlorine),
3) chemicals used to form a coating on the wood surface (Ex. sodium silicate),
4) chemicals that increase the thermal conductivity of wood (Ex. metal alloys),

5) chemicals that dilute the combustible gases coming from the wood with non-combustible gases (Ex. dicyandiamide and urea), and
6) chemicals that reduce the heat content of volatile gases (Ex. inorganic additives).

Rowell (2005) added that, in most cases, a given fire retardant operates by several of the above mechanisms and further research must be conducted to determine the effectiveness and role of these mechanisms in fire retardants.

2.1.3 Performance in Earthquake Events

Wooden structures are especially relevant in earthquake prone countries. Ramirez and Peek-Asa (2005) noted that cases of entrapment during high-intensity earthquakes are higher in concrete structures, compared to wooden structures in which entrapment frequencies are much lower since wooden structures are less vulnerable to collapse. Similar information, was gathered by Doğangün et al. (2006). Doğangün et al. (2006) discussed the use of traditional wood frame buildings in Turkey that were used until approximately 1960. The Turkish community strayed from these traditional buildings and began to practice masonry. However, Doğangün et al. (2006) outlines the regret following the earthquakes in 1999, which inflicted a high level of damage to these concrete buildings as they preformed poorly under the stress of the earthquakes as the plaster would crack and crumble. Ultimately, the paper concludes that wooden structures preform much better during earthquake conditions due to the flexible ability of wood.

Another good example of the performance of mass timber structures during earthquake events is the earthquakes in New Zealand. Buchanan 2014 outlined the superior performance of mass timber structures during the 2010 and 2011 earthquakes in New Zealand. Simply put, the masonry buildings failed and crumbled but the solid wood and EWP buildings did not sustain any serious damage and remained structurally sound. The analysis of the performance of glulam and other EWP during earthquakes is pertinent to this thesis because shear strength is a property that occurs in earthquake situations.

2.1.4 Insulation Characteristics

The Wood Handbook (1940) discusses the superior insulation characteristics of wood in comparison to other building materials. The Wood Handbook states, "Wood, however, possesses the best insulation properties of any of the basic structural materials now commonly used." The book also noted that the insulating value varies with different species with the lighter species having enhanced insulation properties. Similarly, Hale (1951) explained that wood is prized for its insulating effect in house construction, since it does not conduct heat as rapidly as most common building materials. Therefore, if constructed properly, wooden houses can be economically heated during cooler weather. Pickett (2003) stated the R-values for softwood and hardwood are 1.41/inch and 0.71/inch, respectively. This is compared to other building materials such as poured concrete and steel, which have R-values of 0.08/inch according to Colorado Energy (2016). Figure 2 depicts the enhanced insulation properties of wood.

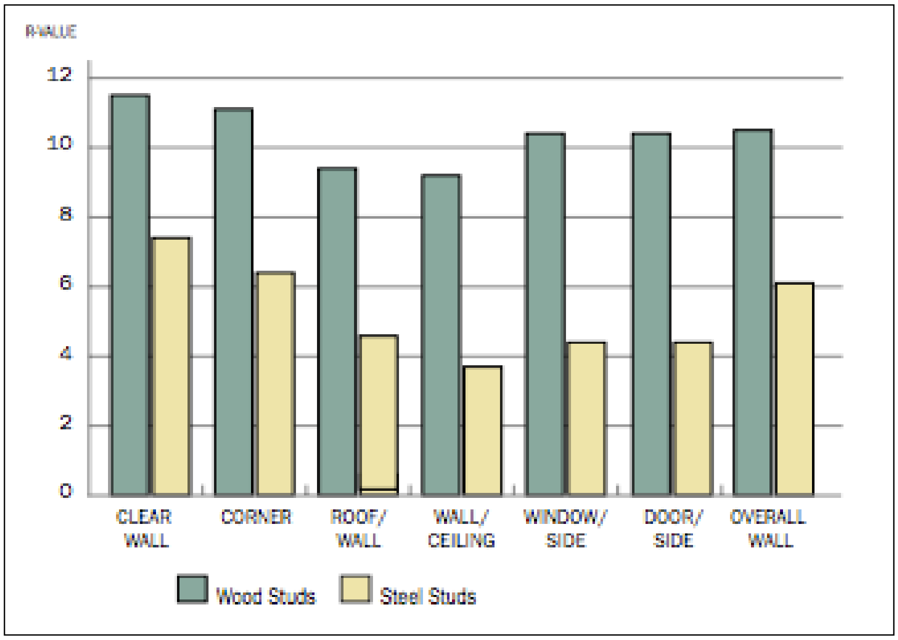


Figure 2. Thermal resistances of wall components with R-12 insulation.

Source: Council 2002

2.1.5 Thermal Conductivity

Hale (1951) and The Wood Handbook (1940) both discussed the thermal conductivity of wood. The two publications defined thermal conductivity as an inverse measure to the insulating value of wood and is the measure of the amount of heat in British Thermal Units that will flow in one hour through one square foot of homogenous material one inch thick for a difference in temperature between opposite surfaces measured in Fahrenheit. In both cases, Hale and the Wood Handbook stated that the heavier the woods (denser hardwood species) had less insulating effect. Hale attributed this fact to the cellular nature of the wood and stated that the lighter woods (softwoods) contain the greatest proportion of closed air spaces in relation to the solid substance of the cell walls.

2.1.6. Economics

Dunn (2015) studied the economic benefits of using wooden structures compared to conventional material-built structures. He found that in all of the cases he analyzed, the timber structural solutions were significantly cheaper to construct (figure 3). He also concluded that the greatest potential benefits to the timber industry are in the industrial shed, aged care and office building markets.

Costed building type	Cost of structural solution		Cost savings of timber compared to traditional structure
	Timber	Traditional	
7 Storey office building	LVL $6,387,913	Concrete $7,289,508	-$901,595 (-12.4%)
8 Storey apartment building	CLT $5,015,705	Concrete $5,126,183	-$110,478 (-2.2%)
2 Storey aged care facility	Timber frame $697,020	Steel frame $809,620	-$112,600 (-13.9%)
Single storey industrial shed	Timber portal frame $216,342	Steel portal frame $238,861	-$22,519 (-9.4%)

Figure 3. Cost savings for each building type comparing EWP and concrete.

Source: Dunn 2015

In addition to the cost savings associated with using wood, there is a notion that is widely accepted that concurs wood is just simply more aesthetically pleasing. Planet Ark (2016) states that studies have concluded being exposed to wooden products can actually lower stress and increase human interaction. Fell (2010) and Burnard and Kutnar (2015) both studied this concept and had similar results. In both cases it was concluded that individuals exposed to wood had reduced stress levels especially when tasked with a stressful undertaking. Knowing this, the addition of more wood-based design paradigms would have a positive effect on human health.

2.2. HISTORICAL WOOD UTILIZATION

Throughout history, the unique characteristics and naturally occurring abundance of trees has made wood an ideal material for houses, furniture, niche products and other structures (i.e. bridges, ships…etc.). Miller (1999) discussed how certain types of wood were used historically. Some of his examples included: white oak – ship construction and bridges, black walnut – furniture and cabinets and hickory – handles and striking tools. Furthermore, Miller stated that, "what the early builder or craftsman learned by trial and error became the basis for deciding which species were appropriate for a given use in terms of their characteristics." This statement has retained its validity as many of these wood species are still used in modern day society for the same products. However, Miller (1999) added that declining old growth forests has gradually been reducing the availability of large clear logs (i.e. minimal knots) for things like lumber and veneer. Wood is a very good engineering material and advances in technology will only increase utilization and make it even more useful.

Youngs (2009) wrote about the historical uses of wood and how it differed through time and contrasting geographies. Youngs (2009) documented that, historically, wood was used as both a fuel and a raw material. For instance, sledges and wheels for transportation were constructed of wood in 3000 – 4000BC. Youngs (2009) also outlined the historical usefulness of wood for construction purposes. He stated that for thousands of years, in heavily forested areas, solid wood wall homes were built and log cabins were also established. However, knowing that the availability of large, high quality logs was diminishing but the demand for them was steady meant that there had to be a shift in the house construction industry. Hale (1951) noted that around the Medieval time period, timber – frame house construction was popular as it provided both a robust and aesthetically pleasing structure that was relatively easy to build. This form of house construction is still prevalent in today's society; however, tools have evolved over time to make the process even more efficient.

2.3 BUILDING CODES AND RESTRICTIONS

Although wood is regarded as a superior building material, there are a number of restrictions and codes that often make it difficult to build large structures exclusively out of wood. Many factors must be considered when designing and constructing wood buildings, including structural, insulation and moisture. Canadian Architect (2014) stated that for many years Canada has been limited to four storey wood buildings, which has hindered the commercial use of wood in large structures. However, Canadian Architect noted that these restrictions were changing, and wood structures were in increasing demand.

Givetash (2016) documented the efforts in British Columbia to push the building codes for wooden structures. In 2009 provincial codes only permitted wood structures to reach six storeys (similarly in Quebec and Ontario), however, new research and engineering has allowed provinces to push the boundaries. British Columbia is leading the way by constructing an unprecedented 18-storey wood structure at the University of British Columbia. Givetash (2016) stated that, "Brock Commons is intended to show both developers and the public that wood can be effective as steel and concrete, better for the environment and support the country's forest industry."

2.4 ENGINEERED WOOD PRODUCTS

2.4.1 Engineered Wood Products

The term engineered wood products (EWPs) is an umbrella term used to identify materials intended for structural use. Thelandersson and Larsen (2003) stated that the wood constituents for EWPs can be sawn laminations, veneers, strands, flakes or sawdust. These components are then bonded together to form specialized timber structures of variable size and shape. Thelandersson and Larsen (2003) concluded that EWPs have several advantages, these include:

1) They can be produced in sizes which are not limited to tree dimensions,
2) Efficient utilization of raw wood material,
3) Strength reducing effects present in solid wood can be more or less neutralized,
4) Dimensional stability is significantly better than sawn timber, and
5) Easily adapted to market requirements.

Although the benefits of EWPs are plenty, a possible disadvantage could be that they decrease the "natural" image of wood since they are engineered.

2.4.2 The Future of Engineered Wood Products

With the movement toward greener solutions and environmental responsibility, EWPs have become a major component in many building sectors. Although EWPs have been around for many years, they are currently streamlining the trend toward sustainability. Anderson (2008) stated that EWPs have become very abundant in newer homes and other structures. He also noted that these products are quite popular compared to traditional sawn lumber since they are generally easy to install and have multiple benefits from an engineering standpoint (i.e. longer spans, enhanced strength properties, stability in service), therefore, these engineered products are economically advantageous because labour costs are reduced. Youngquist (1999) also discussed wood-based composites (or EWPs). One of his major conclusions was the fact that solid wood is highly variable and properties are subject to change. The inherent variability of wood can be more or less controlled in the processing of composites, which is a major benefit when building with wood.

McKeever (1997) discussed the shift in timber resources in the United States during the past 50 years. He stated that much of the old-growth timber has been harvested and the remaining timber is now smaller in diameter and lower in quality. Knowing this, McKeever (1997) determined species that were previously deemed undesirable are now being called upon to augment the reduced supply of desired species. He attributes the shift from solid sawn wood to EWPs to two main reasons: 1) consumption levels beginning to exceed timber supply and 2) the consequential cost increases. The ability to utilize “throw away” trees species in EWPs is one of the primary advantages of EWPs. Finally, McKeever outlined the primary EWPs including oriented strand board (OSB), laminated veneer lumber (LVL), glued-laminated timber (glulam) and I-joists.

2.4.3 Wood Adhesion and Adhesives

According to Skeist and Miron (1990) and River (1994), wood-bonding dates back at least 3,000 years to the Egyptians and adhesive bonding goes back to early mankind. Skeist and Miron (1990) identified multiple advantages of adhesive bonding that are pertinent to EWPs, these included:

1) Thin films/fibers that may not be combined using other techniques are readily bonded with adhesives,
2) Stresses are distributed over wider areas,
3) Enhanced strength to weight ratios can be achieved,
4) Glue lines provide electrical insulation, and
5) Glue lines can act as moisture barriers.

The Wood Handbook (2010) identified several factors that dictate the efficiency of glued joints. The kind of wood, glue, details of gluing, types of joints, conditioning of the joints and the protection when in service are all factors contributing to wood bonding.

Frihart (2005) stated that understanding how an adhesive works/performs is not a science on its own, instead, it is a combination of many sciences. He also detailed the three general steps to adhesive bonding, these included:

1) Preparation of the surface to provide ideal interaction between the adhesive and the substrate,
2) Formation of molecular-level contact between the adhesive and surface, and
3) Solidification or curing of the adhesive.

Each of these steps must occur in order to achieve successful bonding. Frihart (2005) added that adhesives used for laminating lumber or finger jointing can be either heat cured or room temperature cured and that the cost of these adhesives is critical since the thickness of bonded wood has decreased.

Kennedy (1951) documented that there are many different types of wood glues on the market and their usage depends on its desired service. The four main types of glue are casein, urea-formaldehyde resins, phenol-formaldehyde resins, and resorcinolphenol-formaldehyde resins. Additionally, there are some newer glues on the market that are frequently used. A few examples of newer glues include methylene diphenyl diisocyanate (MDI) and polyvinyl acetate (PVA). Kennedy stated that each type of glue has advantages and disadvantages depending on where it will be used. For instance, some glues are cheaper, preform better in water or cure at different temperatures. For example, urea-formaldehyde resins preform much better in the presence of water compared to casein resins. So the type of glue truly depends on the environment the glue will be exposed to during service.

2.5 GLUED LAMINATED TIMBER (GLULAM)

2.5.1 History of Glulam

Moody et al. (1999) and Kennedy (1951) state that glulam did not achieve a significant proportion in the industry until World War II. They noted that it was the shortage of steel and concrete for construction of large military and civil buildings that really brought glulam to fruition.

The advantages of adhesive bonding outlined by Skeist and Miron (1990) are directly related to glulam and are similar to advantages of glulam documented by other authors. Kennedy (1951), Moody et al. (1999) and Berglund and Rowell (2005) all identified the same advantages of glulam:

1) Size is not limited to tree size,

2) Stronger (see figure 4),

3) Use of low-grade lumbers,

4) Use of small trees (too small for conventional sawmilling),

5) Curved members may be constructed,

6) Environmentally friendly, and

7) Aesthetically pleasing.

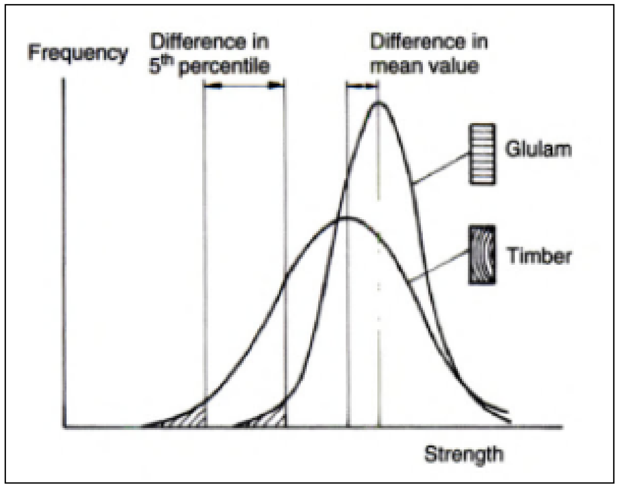


Figure 4. Probability density functions for solid wood and glulam.

Source: Thelandersson and Larsen (2003)

In the construction industry, glulam timber is being rapidly adopted for use as beams, posts, girders, columns and roofing systems (Leitch 2016). Due to recent changes in building codes across Canada, glulam timber has the capacity to rapidly fill these roles.

2.5.2 Standards and Testing Glulam

In order to enhance the utilization of glulam in modern construction, it must meet certain standards regarding its durability in service. It must be made certain that these timber structures will not fail when in service. According to APA (2003), the most recent standard for manufacturing glulam, for commercial use, is ANSI/AITC Standard A190.1 - 02, which took effect in 2002. ANSI (2002) states that the purpose of this standard is to 1) establish nationally recognized requirements for production, inspection, testing and certification of glulam and 2) provide all parties with basis for common understanding of the characteristics of this product. Some general requirements detailed in the standard include dimension tolerance (i.e. width and length), tolerance for straightness, tolerance for squareness, wood species used, moisture content, jointing and adhesives.

There are a number of different tests that can be done on glulam timber. These tests include modulus of elasticity/rupture (MOE/MOR), hardness, screw and nail pull, density, compression and shear strength of glue lines. Each test produces important information about a given piece of glulam and determines where it should be put into service. This current study is focused on shear strength of the glue lines.

2.5.3 Shear Strength Testing

ASTM (2003) provides the standard for shear testing by compression loading. The standard designation is D 905 – 03. The standard outlines the scope of this test, which is to determine the shear strength of adhesive bonds when tested under specific conditions and loading in compression. The testing machine may not have a capacity less than 6810 kg in compression and the shearing tool must have a self-aligning seat to ensure uniform lateral distribution of the load. The standard also specifies the test sample size: 2” x 1.5” x 1 ¾” (figure 5).

In order to observe the difference in shear strength between clear black spruce and glulam, published results must be considered. Early shear strength results by the Wood Handbook (1940) documented that black spruce had an average peak load of 19,038 N (at 12% MC). More recently, Wood Handbook (2010) documented a peak load of 8,500 Kpa, which is 21,920 N (at 12% MC). Shear strength values could be found for glulam timber.

This current study is looking at the shear strength of Glulam produced from small diameter black spruce trees. The individual glued pieces in the product are 1” x 2” pieces. End joints between pieces are finger jointed. Shear tests were conducted on the glue lines between individual pieces in the product.

3 MATERIALS AND METHODS

Due to the nature of the glulam boards, the samples (replicates) for this study were 2" x ¾" x 1 ¾". The width of the sample was half the size of the standard.

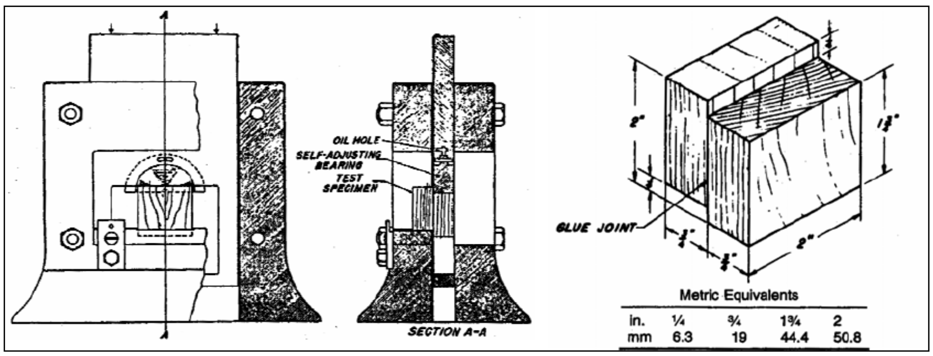


Figure 5. Shearing tool and ASTM standard dimensions for test replicates (ASTM 2008).

3.1 MATERIALS

Five glulam bolts from a Quebec based glulam facility were used. The glulam bolts were constructed with 1" x 2" pieces of *Picea mariana* Marsh. The Wood Mizer LT40 portable sawmill was used to carry out the initial cutting of the bolts and a table saw and band saw were used to recover the sample dimensions needed for testing. The Tinius Olsen universal testing machine and shearing tool in Lakehead University Engineering Testing Facility were used to carry out the shear strength tests. Finally a scanning electron microscope (SEM) was used to observe the glue lines.

3.2 METHODS

3.2.1 Labeling

For the purpose of this study bolts will be deemed samples and each sample block recovered will be referred to as a replicate. Each sample will be identified as G1, G2, G3, G4 and G5. Additional cuts to the original bolts will be identified as boards, therefore, B1, B2, B3 and B4 for each sample (G1, G2 etc.). The labeling scheme for this study is as follows:

Gx (glulam bolt number) – Bx (board number). # (replicate number).

For example, *G1-B3.6* is glulam bolt number one, board three, third replicate (or sample block) as seen in figure 3. From the sawn boards (Bx), 2” x ¾” x 1 ¾” sample blocks (or replicates) were sawn for testing.

3.2.2 Cutting

Each bolt was cut in half at 6 ¼” (figure 6, 7 and 8), one half was sawn into boards that are perpendicular to the glue lines and the other half sawn into boards that were parallel to the glue lines (figure 9). For this study only the parallel sawn boards were utilized, as it was too difficult to extract samples that meet the standards from the perpendicularly sawn boards. Each board was then labeled with the samples to be sawn from each board (figure 10). The table saw was used to cut the boards into the 2” sticks that were measured and marked (figure 11). Once all of the sticks were retrieved from the boards, the individual samples were cut out on the table saw using a 90 degree squaring jig to ensure the end surfaces were perfectly square to the sides of the samples (figure 12). Finally, the table saw and band saw were used to cut the blocks saddles out on each end of the sample (one saddle on opposite sides of each end) to fit onto the shear-testing tool (figure 13).

Figure 6. The glulam bolts cut in half.

Figure 7. A glulam bolt being halved at 6 ¼”.

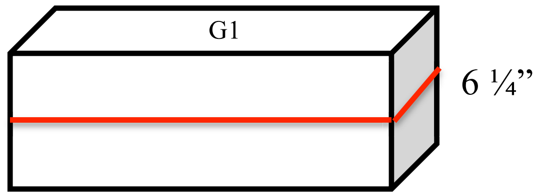


Figure 8. Each sample cut in half at 6 ¼”.

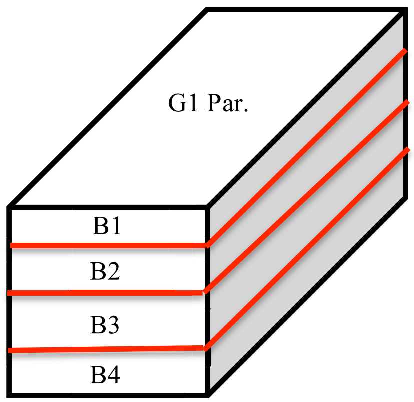


Figure 9. The parallel cuts at 3 7/8”, 2 5/8” and 1 ½” for G1, G2…G5 samples.

Figure 10. Labeling of the replicate blocks on the sawn boards.

Figure 11. 2” sticks sawn using the table saw and ready to be sawn into replicates.

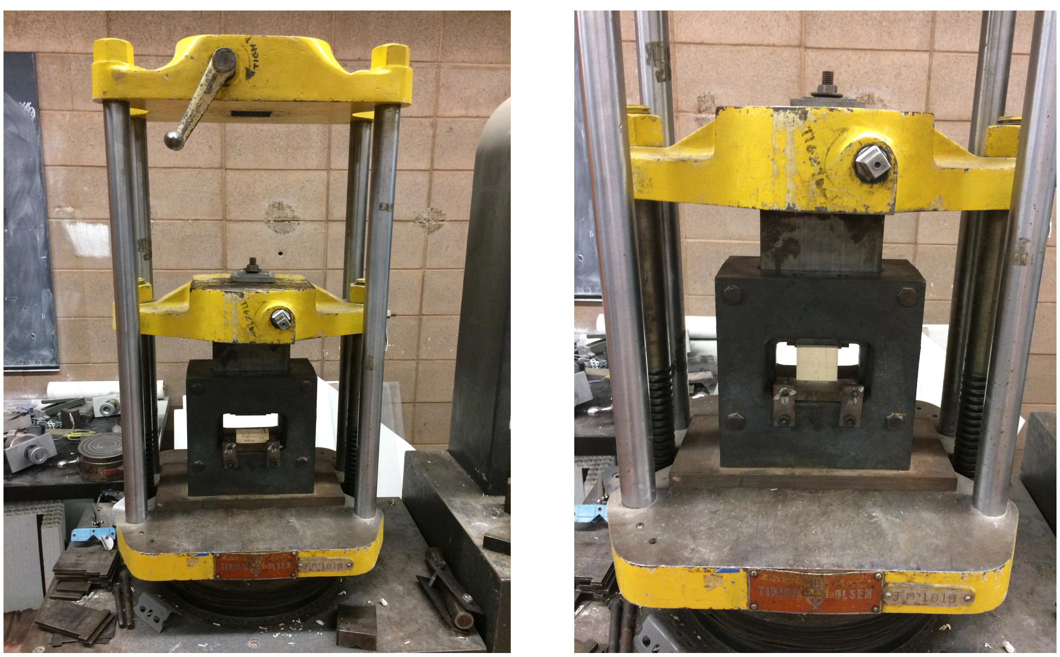
Figure 12. Replicates recovered from the 2” sticks in figure 11.

Figure 13. Replicates at the final dimensions, with saddles cut from each end, ready for testing.

3.2.3 Testing

Testing complied with the ASTM standard (D 905 – 08) for laboratory testing. The shear strength of the adhesives bonds in the glulam replicates was tested. All 50 replicates were placed on the shearing tool individually and the Tinius Olsen testing machine applied force until the glue line sheared (figure 14 and 15). The shear stress at failure was measured in pounds of force (lbf) then converted to Newton's (N) and recorded. Figure 17 displays a test sample after testing.

Figure 14. The Tinius Olsen testing machine and computer setup.



(a) (b)

Figure 15. (a) The Tinius Olsen machine platform with the shear tool mounted on it, (b) the machine shearing a replicate.

1 cm x 1 cm microscopy sections were cut on the glue lines and prepared for examination underneath the scanning electron microscope (SEM). Both transverse and tangential samples were prepared for observation. The samples were sputter coated with pure gold and viewed under the SEM.

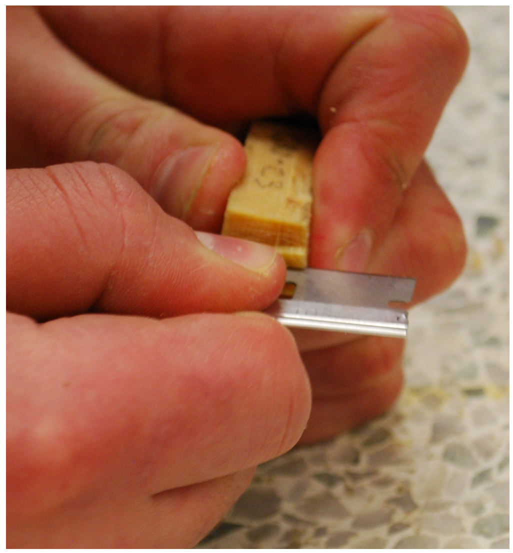


Figure 16. Preparing the 1 cm x 1 cm SEM samples.

4 RESULTS

The statistical results for this report are the interpreted outputs of a one-way analysis of variance (ANOVA) and a Tukey Post Hoc test at the 95% ($\alpha = 0.05$) probability or confidence limit. The primary qualitative result in this study was the shearing of the replicates on the glue as shown in figure 17.

Figure 17. A replicate shorn on the glue line after the test was completed.

Simple stats were run to observe the average load (N) required to shear the glue line within the replicates for each bolt and the corresponding standard deviation. The overall average peak load between the five bolts used in the study was 21,354.59 N (table 1). The Average peak loads are also displayed in figure 23.

Table 1. Summary of average peak load and standard deviation for each bolt.

Bolt	Average Load (N)	Standard Deviation
G1	21263.21	3666.11
G2	23029.86	3748.48
G3	18374.05	4884.82
G4	21439.63	3081.85
G5	22666.21	4602.88
Total	**21354.59**	

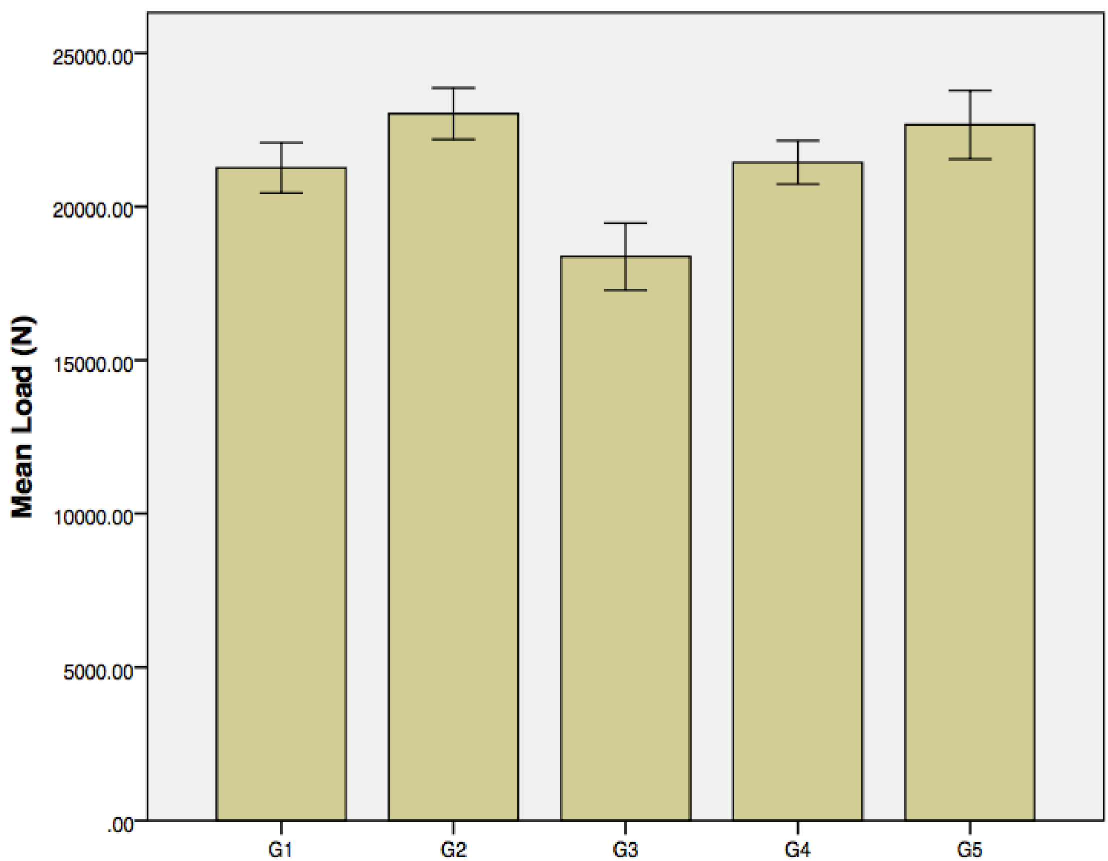


Figure 18. The average peak load (N) for each glulam bolt with error bars representing +/- one standard deviation.

An analysis of variance was run to analyze the ratio of variances and reveal the presence of significant differences in the amount of force required (N) to shear the glue line between the bolt, board and bolt and board interaction. The results are recorded in table 2. At the 95% confidence limit the ANOVA revealed that there was a significant difference in force required (N) in the bolt and board interaction ($F_{calc} = 0.043$, $p < 0.05$). There was also a significant difference in the board variable ($F_{calc} = 0.006$, $p < 0.05$) and the bolt variable ($F_{calc} = 0.002$, $p < 0.05$).

Table 2. Analysis of variance (ANOVA) results.

Dependent Variable: Load (N)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5.40E+8[a]	9	5.995E+7	4.263	.000
Intercept	4.24E+10	1	4.24E+10	3018.309	.000
Bolt	2.537E+8	4	6.342E+7	4.510	.002
Board	1.548E+8	2	7.738E+7	5.503	.006
Bolt * Board	1.193E+8	3	3.978E+7	2.829	.043
Error	1.209E+9	86	1.406E+7		
Total	4.54E+10	96			
Corrected Total	1.749E+9	95			

a. R Squared = .309 (Adjusted R Squared = .236)

To determine where the significant differences are found with the ANOVA, a Tukey Multiple Comparisons of Mean Post Hoc test was run (table 3). This test showed that the significant differences were found between G2 and G3 ($F_{calc} = 0.002$, $p < 0.05$) and G3 and G5 ($F_{calc} = 0.007$, $p < 0.05$).

Table 3. Tukey Multiple Comparisons of Mean Post Hoc test results.

Dependent Variable: Load (N)

Tukey HSD

(I) Bolt	(J) Bolt	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
G1	G2	-1766.65	1185.827	.572	-5070.95	1537.655
	G3	2889.163	1185.827	.116	-415.142	6193.467
	G4	-176.419	1201.328	1.000	-3523.92	3171.081
	G5	-1402.99	1237.037	.788	-4849.99	2044.008
G2	G1	1766.650	1185.827	.572	-1537.65	5070.955
	G3	4655.81*	1185.827	.002	1351.508	7960.117
	G4	1590.231	1201.328	.677	-1757.27	4937.731
	G5	363.6566	1237.037	.998	-3083.34	3810.658
G3	G1	-2889.16	1185.827	.116	-6193.47	415.1420
	G2	-4655.81*	1185.827	.002	-7960.12	-1351.51
	G4	-3065.58	1201.328	.089	-6413.08	281.9183
	G5	-4292.16*	1237.037	.007	-7739.16	-845.154
G4	G1	176.4191	1201.328	1.000	-3171.08	3523.919
	G2	-1590.23	1201.328	.677	-4937.73	1757.269
	G3	3065.582	1201.328	.089	-281.918	6413.081
	G5	-1226.57	1251.905	.864	-4715.00	2261.856
G5	G1	1402.993	1237.037	.788	-2044.01	4849.995
	G2	-363.657	1237.037	.998	-3810.66	3083.345
	G3	4292.16*	1237.037	.007	845.1544	7739.157
	G4	1226.574	1251.905	.864	-2261.86	4715.005

Based on observed means.
The error term is Mean Square(Error) = 14061851.549.
*. The mean difference is significant at the 0.05 level.

Figures 19 through 23 are the resulting photos taken during scanning electron microscopy. Photos were taken on the transverse and tangential plains.

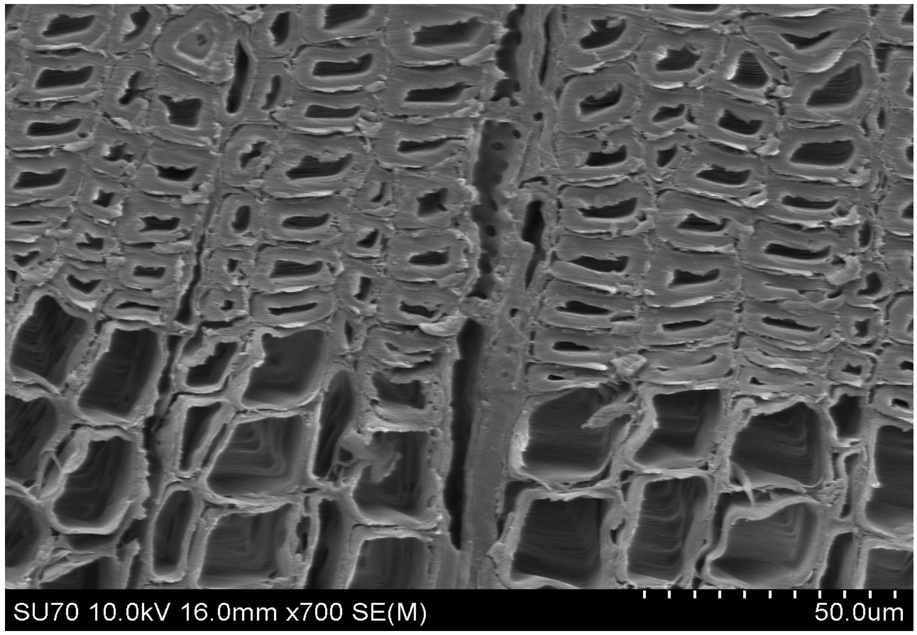


Figure 19. Transition from early wood to late wood on the transverse plain.

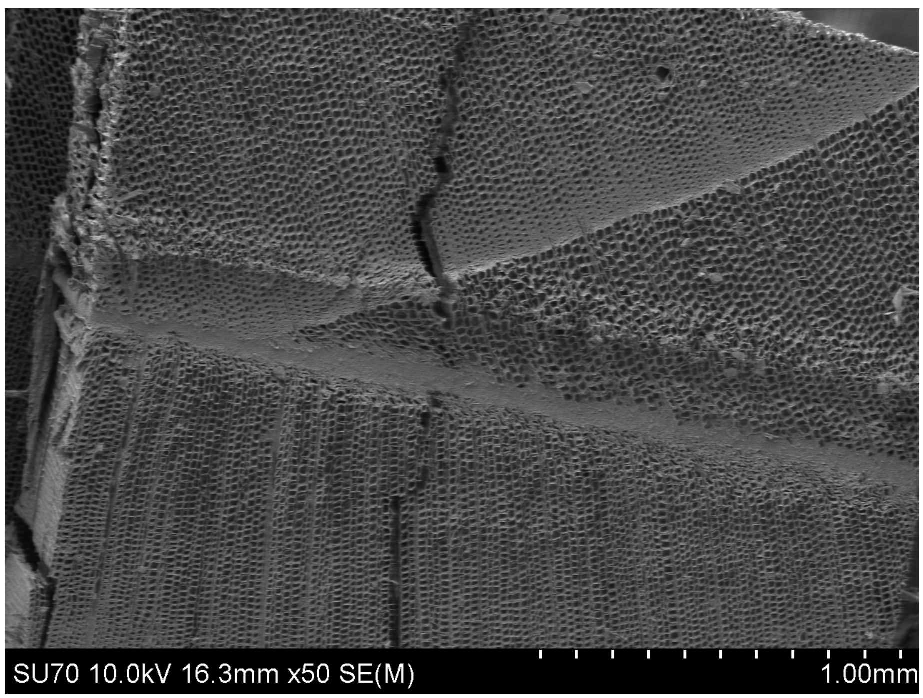


Figure 20. A general view of the transverse plain with a glue line through the middle.

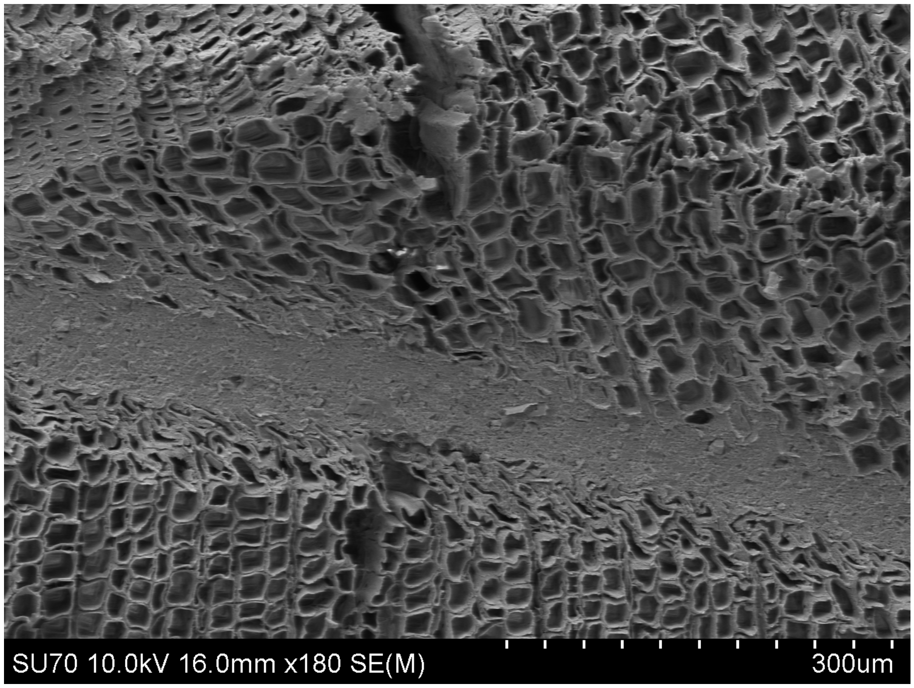


Figure 21. A zoomed-in picture of the glue line in figure 20.

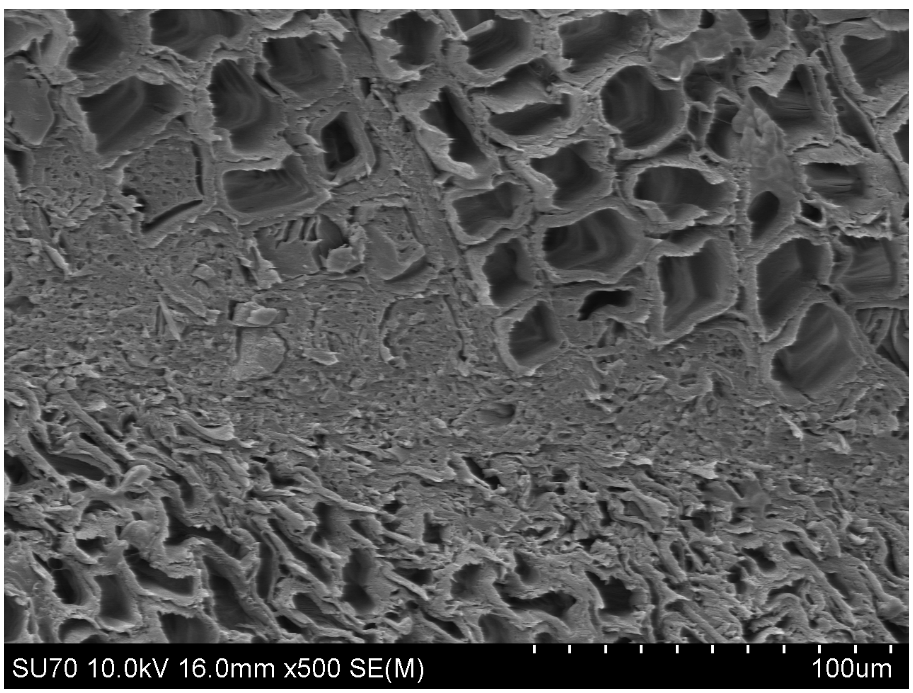


Figure 22. The glue penetrating the spaces between wood cells.

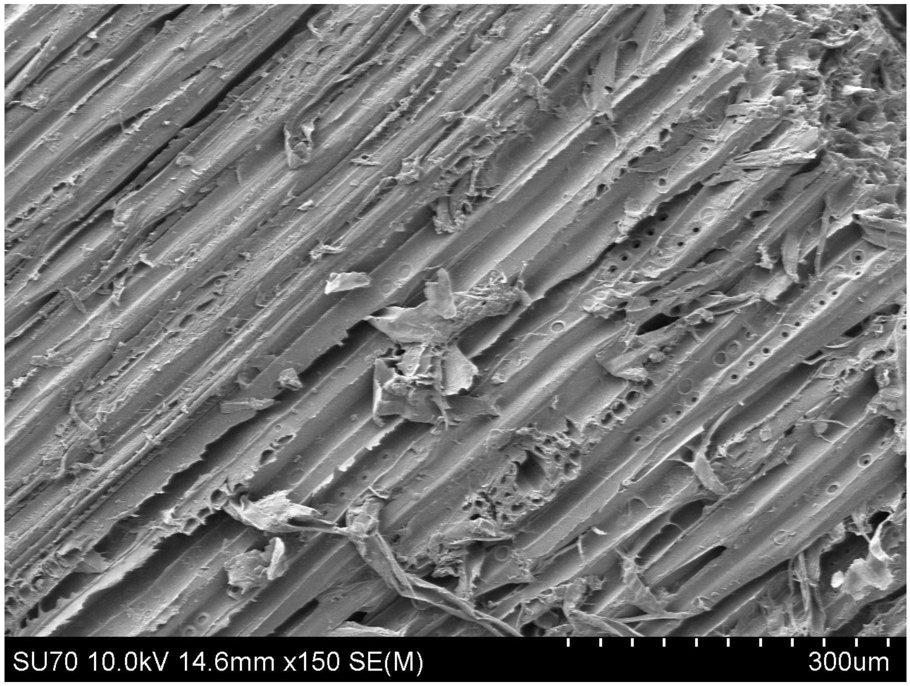


Figure 23. Tangential view of glulam displaying rays and fusiform rays.

5 DISCUSSION

The results generated in this study were originally recorded in pounds of force (lbf) and converted to newtons (N). However, the majority of published values found were expressed as either kilopascals (Kpa) or pounds of force per square inch (lb/in^2). Therefore, I converted these values to N to simplify data analysis. For instance, the published value for clear black spruce from the Wood Handbook (2010) was 8,500kpa, so this value was converted to 1,232 lb/in^2. Then I multiplied this value by four because my samples were four square inches and produced the value 4,298 lbf. Finally, this value was converted to N by multiplying by 4.45, which resulted in a value of 21,920 N.

Compared to the published value for clear black spruce (21,920 N), the results generated in this study were almost identical with an overall average peak load of 21,354 N. Based on this result it can be concluded that the shear strength of clear black spruce compared to the glue line shear strength was not significant. Although the results do show that there is not a significant difference in shear strengths it is important to note that the advantages of glulam timber are at a greater scale. Although shear strength values did not differ in this study with regards to clear wood, glulam strength properties are cumulative and would show this when tested at a larger scale. It is the accumulation of strength properties within glulam that give it its enhanced characteristics (Thelandersson and Larsen 2003).

The average shear strength results were fairly consistent amongst the five bolts with the exception of G3, which displayed a significantly lower average peak load. The source of this deviation is unknown. All samples were prepared to standard dimensions. Therefore, the observed difference in average peak load for G3 is unexplainable. However, we can speculate that this bolt may have had an abundance of internal defects, like knots and cracks, which could have affected the peak load values for G3. There are numerous natural characteristics/defects that affect the strength properties of wood. Some of these defects include: knots, specific gravity, annual ring orientation, reaction wood and juvenile wood (Wood Handbook 2010 and Winandy and Rowell 1984). Knots are considered the primary defect in wood. They significantly reduce the strength of wood because the distorted grain passing around them hinders mechanical strength properties (Wood Handbook 2010). If there was an abundance of knots present within the G3 bolt, it may help to explain this variation in peak load values.

Although there was no published values for glulam shear strength, these results showed a fairly high degree of uniformity. The results can be deemed credible due to the fact that 1) they are consistent with the published values for clear wood and 2) with the exception of G3, average peak loads for each bolt were very similar.

The results from the ANOVA test revealed that there was a significant difference in shear strength between bolts, boards and bolt and board interactions. All three variables resulted in a calculated F value below the critical value of 0.05. Therefore, I reject the null hypothesis because there are significant differences in shear strength between the glulam bolts. The differences in strength between bolts could be a result of the inherent variability in wood (Wood Handbook 2010). Different bolts may have varying degrees of defects, which, when sawn into smaller pieces, could have affected the shear strength. Additionally, knowing that the glue laminating process decreases variability in wood strength properties (Thelandersson and Larsen 2003), perhaps the reduction of the bolts into small, individual samples enhanced the variability in strength properties. The board variable was included in the ANOVA test but it was not considered because they were arbitrarily chosen. Running stats on the board variability would not have shown significant results.

To determine the source of significant difference a Tukey Multiple Comparisons of Mean Post Hoc test was run. The results from this test show that the significant differences between bolt 2 and 3 (G2/G3) and bolt 3 and 5 (G3/G5). This significance was identified through the F_{calc} values of 0.02 and 0.07, respectively, which are less than the alpha level 0.05. These results were to be expected based on the results and the average peak loads depicted in figure 23. Prior to statistical analysis it was clear that G3 had a lower average peak load especially compared to G2 and G5, which had the highest average peak loads amongst the five bolts.

We were unable to compare these results to the standard A 190.1 – 02 because they did not supply minimum or required shear strength values.

Tests such as this are crucial for determining the end use of a glulam product. Understanding the maximum amount of force that can be applied to a given piece of glulam at any orientation or load type is of the utmost importance. When a glulam structure is put into service, you must be 100% certain that it will not fail while in service.

The advantages of glulam are numerous. The primary advantages include the usage of underutilized wood, the creation of mass timber structures, stronger products and consistency of properties. The ability to use smaller pieces of wood, that typically would not be used, to construct glulam structures is paramount. Additionally, there are emerging studies surrounding the usage of “throw away” tree species in the neutral access of glulam beams. This could potentially increase our utilization of wood in the forest, which would make the industry even more sustainable.

Since glulam is so versatile in its construction, in can be used to fill as variety of niches. Glulam also allows the creation of mass timber structures that stretch hundreds of feet. This advantage is important because we longer have the abundance of old growth forests to fulfill the need for massive timber structures. The use of glulam means that we are not limited to naturally growing trees and growth patterns. It is undisputed that glulam structures are stringer than clear wood structures do to the accumulation of strength properties resulting from multiple pieces of wood. Moreover, it is this accumulation of smaller pieces that also decreases the variability in a timber structure. Making a wood product more predictable is essential, especially within the construction industry.

6 CONCLUSION

The soaring global population calls for a shift in practices, especially within the construction industry. Sustainable developments and greener solutions are being pushed now more than ever in the face of global climate change. Wood is the only naturally occurring and renewable construction material on the planet and has numerous advantages associated with it. From carbon sequestration (Buchanan 2007) to insulation properties (Hale 1951), wood satisfies all of the criteria for a superior building material. EWP's affirm this notion, as we are now able to enhance our utilization of the forest and create niche timber structures and modified boards. Glulam is now being used more frequently in the development of wooden buildings. British Colombia is currently leading the way after the construction of Brock Towers, an 18-story EWP building on the University of British Columbia campus (Givetash 2016).

It was hypothesized that shear strength values would not be significantly different throughout the bolts during the test. However, this hypothesis was ultimately rejected because all variables had a calculated F value lower than the critical value of 0.05. Despite the rejection of the null hypothesis, the study had promising results. With the exception of one bolt, the average peak loads remained fairly consistent and were similar to published values for clear black spruce.

To improve on this study, I would have ensured that the correct size of samples was used. Although the results are realistic, comparison to a standard is impossible if the dimensions used do not match the required ones. Greater detail and accuracy would have been ideal, however, the time allocated to this study was limited.

7 LITERATURE CITED

American National Standards Institution (ANSI). 2002. ANSI 190.1-02: standard for structural glued laminated timber.

Anderson, J. 2008. Engineered Wood Products. University of Washington. Pp. 1.

APA - The Engineered Wood Association. 2003. Glulam Product Guide, EWS, 440.

American Society for Testing and Materials (ASTM). 2008. D 905 - 08: standard test method for strength properties of adhesive bonds in shear by compression loading. Pp. 25 – 28.

Atlantic WoodWORKS. 2016. Mid-rise wood opportunities for atlantic Canadian urban centers. Nova Scotia. Pp. 7 and 8.

Bendtsen, B. A. 1974. Specific gravity and mechanical properties of Black, Red, and White Spruce and Balsam Fir. U.S. Department of Agriculture Forest Service Forest products Laboratory. Madison, WIS. (FPL-237). Pp. 18.

Berglund, L. and Rowell, R. M. 2005. Wood composites. Handbook of wood chemistry and wood composites. CRC Press. Pp. 280 – 281.

Börjesson, P., and Gustavsson, L. 2000. Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. Energy policy, 28:9. Pp. 575-588.

Buchanan, A. 2007. Energy and CO2 advantages of wood for sustainable buildings. In Institute of Professional Engineers Convention. Pp. 9.

Buchanan, A. 2014. Post-tensioned multi-story timber buildings. University of Canterbury, New Zealand. http://wood-works.ca/wp-content/uploads/3-andy-buchanan-international-wood-symposium-v2.pdf March 27, 2017.

Buckland Timber. 2012. Benefits of glulam. http://www.bucklandtimber.co.uk/about-our-glulam/benefits-of-glulam/. October 17, 2016.

Burnard, M. D. and Kutnar, A. 2015. Wood and human stress in the built indoor environment: a review. Wood Science and Technology, 49:5. Pp. 969-986.

Canadian Archtect. 2014. Changes to Ontario building code allow wood-frame buildings up to six storeys. www.canadianarchitect.com February 8, 2017.

Colorado Energy. 2016. R-value table: insulation values for selected materials. http://www.coloradoenergy.org/procorner/stuff/r-values.htm. Accessed January 15, 2017.

Council, C. W. 2002. Wood-frame housing-A north American marvel. Report No. Building Performance Series, 4.

Doğangün, A., Tuluk, Ö. İ., Livaoğlu, R., and Acar, R. 2006. Traditional wooden buildings and their damages during earthquakes in Turkey. Engineering Failure Analysis, 13:6. Pp. 981-996.

Dong, J., Kaufmann, R. K., Myneni, R. B., Tucker, C. J., Kauppi, P. E., Liski, J., and Hughes, M. K. 2003. Remote sensing estimates of boreal and temperate forest woody biomass: carbon pools, sources, and sinks. Remote Sensing of Environment, 84:3. Pp. 393-410.

Dunn, A. 2015. Final report for commercial building costing cases studies – traditional design versus timber project. Timber Development Association NSW Ltd. Pp.

Fell, D. R. 2010. Wood in the human environment: restorative properties of wood in the built indoor environment (Doctoral dissertation, University of British Columbia).

Frihart, C. R. 2005. Wood adhesion and adhesives. Handbook of wood chemistry and wood composites. CRC Press. Pp. 216-217.

Givetash, L. 2016. Country's tallest wood tower tests building codes. The Canadian Press. June 14, 2016.

Green, D. W., Winandy, J. E. and Kretschmann, D. E. 1999. Mechanical properties of wood. Wood Handbook: Wood as an Engineering Material. 4-8. Pp.

Hale, J. D. 1951. The structure of wood. Canadian woods: their properties and uses. Pp. 96 - 97.

Jirouš-Rajković, V., and Miklečić, J. 2009. Fire retardants for wood. Drvna industrija, 60:2. Pp. 111-121.

Kennedy, D. E. 1951. Glued, laminated construction. Canadian woods: their properties and uses. Pp. 281 – 289.

Leitch, M. 2016. Wood properties. Wood Science: 5c. (PowerPoint).

Low, K., and Burns, K. 2013. Engineered wood products. Agricultural Commodities, 3:1. Pp. 130.

Luyssaert, S., Schulze, E. D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., Philippe, C. and Grace, J. 2008. Old-growth forests as global carbon sinks.Nature, 455:7210. Pp. 213-215.

McKeever, D. B. 1997. Engineered wood products: a response to the changing timber resource. Pacific Rim Wood Market Report, 123:5. Pp. 15.

Miller, R. B. 1999. Characteristics and availability of commercially important woods. Wood Handbook: Wood as Engineering Material. Pp. 1-2.

Moody, R. C. and TenWolde, A. 1999. Use of wood in buildings and bridges. Wood Handbook: Wood as Engineering Material. 16-10, 16-11.

Moody, R. C., Hernandez, R., and Liu, J. Y. 1999. Glued structural members. Wood Handbook: Wood as Engineering Material. 11-3, 11-4.

Perez-Garcia, J., Lippke, B., Comnick, J., and Manriquez, C. 2004. Tracking carbon from sequestration in the forest to wood products and substitution. CORRIM: Phase I Final Report. Module N. Seattle, WA. Pp. 26.

Pickett, R. 2003. The Energy Performance of Log Homes, Log Homes Council, National Association of Home Builders.

Planet Ark. 2016. Make it wood. The benefits of using wood. http://makeitwood.org/benefits-of-wood/. October 16, 2016.

River, B.H. 1994. Fracture of adhesively bonded wood joints. Handbook of adhesives. New York. Chapter 9.

Rowell, R. 2005. Thermal properties. Handbook of wood chemistry and wood composites. CRC Press. Pp. 131.

Rowell, R. M., and Dietenberger, M. A. 2005. Thermal properties, combustion, and fire retardancy of wood. Handbook of wood chemistry and wood composites, CRC Press. Chapter 6. Pp. 136.

Ramirez, M., and Peek-Asa, C. 2005. Epidemiology of traumatic injuries from earthquakes. Epidemiologic reviews, 27:1. Pp. 47-55.

Sathre, R. 2007. Life-cycle energy and carbon implications of wood-based products and construction Doctoral dissertation, Mid Sweden Univ. Pp. 7.

Skeist, I. and Miron, J. 1990. Introduction to adhesives. Handbook of adhesives. Springer US. Pp. 3-20.

Thelandersson, S., and Larsen, H. J. 2003. Timber engineering. John Wiley & Sons. West Sussex, England. Pp. 18-19

Wood Handbook. 1940a. Thermal Insulation. Forest Products Laboratory. U.S. Department of Agriculture. Pp. 300-303.

Wood Handbook. 1940b. Glued wood construction. Forest Products Laboratory. U.S. Department of Agriculture. Pp. 169-172.

Wood Handbook. 2010. Wood as an engineering material. Forest Products Laboratory. U.S. Department of Agriculture.

Youngquist, J. A. 1999. Wood-based composites and panel products. Wood Handbook. Wood as Engineering Material. Pp. 10-1 – 10-2.

Youngs, R. L. 2009. History, Nature, and Products of Wood. Forests and Forest Plants, Vol. 2. Encyclopaedia of Life Support Systems. Pp. 2 and 3.

8 APPENDICES

8.1 APPENDIX I: SHEAR TESTING RESULTS

Sample	Peek Load (lbf)	Converted (N)
G1 - B1.1	4300	19135.00
G1 - B1.2	4445	19780.25
G1 - B1.3	5780	25721.00
G1 - B1.4	5225	23251.25
G1 - B1.5	4690	20870.50
G1 - B1.6	3210	14284.50
G1 - B1.7	4805	21382.25
G1 - B1.8	4275	19023.75
G1 - B1.9	6075	27033.75
G1 - B1.10	5470	24341.50
G1 - B3.1	4890	21760.50
G1 - B3.2	5570	24786.50
G1 - B3.3	5270	23451.50
G1 - B3.4	4770	21226.50
G1 - B3.5	5825	25921.25
G1 - B3.6	5350	23807.50
G1 - B3.7	3440	15308.00
G1 - B3.8	4720	21004.00
G1 - B3.9	3440	15308.00
G1 - B3.10	4015	17866.75

Average (N):	21263.21
STD:	3666.11
Average (lbf):	4778.25
lb sq. inch	1194.5625

Sample	Peek Load (lbf)	Converted (N)
G2 - B1.1	6670	29681.50
G2 - B1.2	5060	22517.00
G2 - B1.3	4795	21337.75
G2 - B1.4	6510	28969.50
G2 - B1.5	4290	19090.50
G2 - B1.6	6490	28880.50
G2 - B1.7	4885	21738.25
G2 - B1.8	5685	25298.25
G2 - B1.9	5800	25810.00
G2 - B1.10	5255	23384.75
G2 - B2.1	4155	18489.75
G2 - B2.2	5300	23585.00
G2 - B2.3	4445	19780.25
G2 - B2.4	4010	17844.50
G2 - B2.5	5065	22539.25
G2 - B2.6	5190	23095.50
G2 - B2.7	5340	23763.00
G2 - B2.8	5710	25409.50
G2 - B2.9	3515	15641.75
G2 - B2.10	5335	23740.75

Average (N):	23029.86
STD:	3748.48
Average (lbf):	5175.25
lb sq. inch	1293.8125

Sample	Peek Load (lbf)	Converted (N)
G3 - B1.1	3840	17088.00
G3 - B1.2	4245	18890.25
G3 - B1.3	4595	20447.75
G3 - B1.4	4150	18467.50
G3 - B1.5	5855	26054.75
G3 - B1.6	4725	21026.25
G3 - B1.7	4450	19802.50
G3 - B1.8	5630	25053.50
G3 - B1.9	5450	24252.50
G3 - B1.10	4435	19735.75
G3 - B2.1	4595	20447.75
G3 - B2.2	4780	21271.00
G3 - B2.3	4365	19424.25
G3 - B2.4	2940	13083.00
G3 - B2.5	2840	12638.00
G3 - B2.6	2170	9656.50
G3 - B2.7	4160	18512.00
G3 - B2.8	2395	10657.75
G3 - B2.9	2140	9523.00
G3 - B2.10	4820	21449.00

Average (N):	18374.05
STD:	4884.82042
Average (lbf):	4129
lb sq. inch	1032.25

Sample	Peek Load (lbf)	Converted (N)
G4 - B2.1	5030	22383.5
G4 - B2.2	4055	18044.75
G4 - B2.3	5000	22250.00
G4 - B2.4	5535	24630.75
G4 - B2.5	5515	24541.75
G4 - B2.6	3325	14796.25
G4 - B2.7	4100	18245.00
G4 - B2.8	6085	27078.25
G4 - B2.9	4335	19290.75
G4 - B2.10	4205	18712.25
G4 - B3.1	4730	21048.50
G4 - B3.2	4900	21805.00
G4 - B3.3	pre-exsisting crack	NO VALUE
G4 - B3.4	4385	19513.25
G4 - B3.5	5805	25832.25
G4 - B3.6	4730	21048.50
G4 - B3.7	5680	25276.00
G4 - B3.8	4780	21271.00
G4 - B3.9	4820	21449.00
G4 - B3.10	4525	20136.25

Average (N):	21439.63
STD:	3081.848704
Average (lbf):	4817.894737
lb sq. inch	1204.473684

Sample	Peek Load (lbf)	Converted (N)
G5 - B1.1	4445	19780.25
G5 - B1.2	4620	20559.00
G5 - B1.3	3435	15285.75
G5 - B1.4	5850	26032.50
G5 - B1.5	5760	25632.00
G5 - B1.6	3065	13639.25
G5 - B1.7	5735	25520.75
G5 - B1.8	3955	17599.75
G5 - B1.9	5055	22494.75
G5 - B1.10	5180	23051.00
G5 - B3.1	pre-existing crack	NO VALUE
G5 - B3.2	test sample	NO VALUE
G5 - B3.3	5620	25009.00
G5 - B3.4	6975	31038.75
G5 - B3.5	5430	24163.50
G5 - B3.6	4530	20158.50
G5 - B3.7	6625	29481.25
G5 - B3.8	4785	21293.25
G5 - B3.9	test sample	NO VALUE
G5 - B3.10	5525	24586.25

Average (N):	22666.21
STD:	4602.878941
Average (lbf):	5093.529412
lb sq. inch	1273.382353