SUSTAINABILITY IN THE BUILT ENVIRONMENT – EVALUATING SPLINE CONNECTIONS IN EASTERN HEMLOCK CROSS LAMINATED TIMBER

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ABSTRACT

Wood buildings provide healthy indoor environments, energy efficient building design, low-carbon and resource efficient technologies, and many other benefits to the built environment. My project aims to foster the use of cross laminated timber (CLT), an engineered wood panel used in the construction of large-scale buildings and made from adhering dimensional lumber in a layered, crosswise manner. Eastern Hemlock (*Tsuga Canadensis*) lumber was chosen because this tree species is abundant in New England yet underutilized as a forest product, and thus a good candidate for local production of CLT. The goal of my project is to quantify monotonic and cyclic behavior of panel to panel assemblies of single surface splines (e.g. strips of lumber): (i) with adhesive and (ii) without adhesive. I hypothesize that the panel to panel assemblies that have adhesive will perform stronger and stiffer because including adhesive in the connection will increase shear resistance and improve the overall connection ability to resist loads. A specimen consists of three Eastern Hemlock CLT panels with two single surface splines and four screws connecting them. The specimens were fabricated using standard shop tools: a chop saw, a band saw, a drill, and others. Laminated veneer lumber panels were attached to steel rods that held down the specimen while the head of the MTS testing machine was attached to the top of the specimen. This allowed for static and cyclic loading. Yield and deformation data were collected. It was found that the glued specimens performed stronger and stiffer but responded with more variability than the non-glued specimens.

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1 INTRODUCTION

A major advantage of incorporating wood in the design of modern buildings is environmental sustainability. Specifically, wood structures can help further energy efficiency, atmosphere protection, water conservation, material & resource efficiency, and a healthy indoor environment.

My project focused on a specific engineered wood product called cross laminated timber (CLT). Cross laminated timber is a panel of wood created from adhering layers of lumber together in a crosswise manner. In the hopes of making advancements in the field of wood engineering and increasing the popularity of wooden structures, my project evaluated which connections worked best in CLT made from Eastern Hemlock (*Tsuga Canadensis*). Eastern hemlock was specifically chosen to be used in this project since it is a good candidate for local production of CLT due to its status as a low-value species and its abundance in New England.

The aim of my project was to evaluate panel to panel assemblies of single surface splines (e.g. strips of lumber) in the following four conditions: (i) monotonic testing with adhesive, (ii) monotonic testing without adhesive, (iii) cyclic testing with adhesive, and (iv) cyclic testing without adhesive. A singular specimen is comprised of 3 CLT panels and 2 single surface splines connecting them. There were #8 screws to connect the splines and the CLT panels together. The assemblies were subjected to static and cyclic loadings. The specimen was set up in an MTS testing machine and yield load and deformation data was collected.

The scientific problem that this project pursued was quantifying how adhesive improves single surface splines of panel assemblies. I hypothesized that the panel to panel assemblies that have adhesive will significantly improve static and cyclic strength and stiffness because including adhesive in the connection will increase the ability to resist the loads applied on the specimen and prevent the specimen from breaking as easily.

The initial task of this project was to fabricate panel to panel assemblies of eastern hemlock by cutting down CLT panels and then creating notches for the splines. The next task was to fabricate the splines by cutting the plywood. The splines were then attached to the CLT panels in an assembly that was comprised of three CLT panels and two single surface splines that connected the CLT panels together. Adhesive was applied to half of the specimens while no adhesive was added to the other half.

The experimental test set-up for the CLT assembly in the MTS testing machine is outlined as follows. Two panels of laminated veneer lumber and steel rods were needed to fix the two outer panels of CLT down to the T-slot table under the MTS testing machine. A connection on the inner CLT panel was attached to the head of the testing machine so that cyclic and static loading could be applied. Once the specimen was properly set up in the testing machine, two sets of data were collected. One for static loading and one for cyclic loading was gathered for analysis.

Climate change is a considerable problem in today's world and one key to solving this rising threat is to implement environmental sustainability in our lives, in our transportation, and especially in our infrastructure. One way to practice environmental sustainability in the construction of our infrastructure is to incorporate wood in our buildings. While steel and concrete buildings are more prevalent in today's society, wood structures have a few key advantages compared to these building materials. Wood buildings can help further water conservation, resource efficiency, energy efficiency, a healthy indoor environment, and many other aspects of sustainable construction. Compared to a steel and concrete building, a wooden building emits less greenhouse gas emissions. Wood can also stand up to steel and concrete when it comes to strength and stiffness through engineered wood products. Cross laminated timber is one of these engineered wood products. However, there is not sufficient research done on cross laminated timber connections made out of eastern hemlock.

This project aims to make progress in the timber engineering field by testing eastern hemlock CLT panels joined together with single surface splines and screws subjected to cyclic and static loading. By testing the panels under four conditions: i) monotonic testing with adhesive, (ii) monotonic testing without adhesive, (iii) cyclic testing with adhesive, and (iv) cyclic testing without adhesive, we gained more knowledge in terms of eastern hemlock CLT connections. By learning more about these connections, the timber industry can more readily use eastern hemlock in construction applications.

2 SUMMARY OF WORK OF PREVIOUS RESEARCHERS

Today, buildings are generally constructed using steel and concrete; timber is an alternative material gaining popularity. Specifically, cross-laminated timber (CLT) is revolutionizing the way architects and engineers design structures. Not only does it have environmental benefits, it also features a variety of advantages that make it a desirable construction material such as strength, stiffness, and design flexibility. There are many different factors that affect the performance of CLT in buildings and structures. One factor that greatly affects CLT performance are the mechanical connections with which CLT buildings are constructed. There are a variety of different structural connection systems with different fasteners which are used to attach CLT panels together in a building. This literature review will discuss four common mechanical connections: nails, screws, bolts, and splines.

2.1 CROSS LAMINATED TIMBER

Cross-laminated timber (see Figure 1) consists of an uneven number of layers of timber stacked in a crosswise manner and adhered to each other on their wide faces. Cross-laminated timber began in Europe but gradually grew to become a worldwide product (Brandner et al. 2016). CLT is quickly becoming a competitor in the construction material market, especially when compared to concrete and steel. CLT has high in-plane and out-of-plane strength and stiffness properties which give it capabilities similar to a concrete slab ("The CLT Handbook" 2013). Resistance against shear in-plane and tension perpendicular to grain can be achieved when CLT is used. In terms of preparing and manufacturing CLT, there is fast assembly and construction times due to pre-fabrication and assembly of larger sized components. It can be used in the upgrading of old or existing buildings as well (Brandner et al. 2016).

Figure 1. A photo of cross laminated timber. Taken from: Hedmond, S. (2017, December 5). America's 'Largest' Mass Timber Building is Under Construction in Oregon. Retrieved from https://www.constructionjunkie.com/blog/2017/12/3/americas-largest-mass-timber-building-is-under-construction-in-oregon.

2.2 CLT ATTRIBUTES

Differing from lightweight wood joisted floors and concrete slab floors, CLT floors have to be specially designed. Vibration performance of CLT floors can be predicted through a proposed design method from FPInnovations. The FPInnovations method worked on the understanding that controlling vibrations involved limiting the combination of longitudinal stiffness and mass of CLT floors ("The CLT Handbook" 2013).

Although many raise the question of ease of combustibility when it comes to CLT buildings, studies on testing the fire resistance of such buildings have shown that they can limit fire spread beyond the point of origin. In fact, there are three reasons why CLT panels provide great fire resistance (see Figure 2). As stated by the CLT Handbook (2013), "This is due to the inherent nature of thick timber members to char slowly at a predictable rate, allowing massive wood systems to maintain significant structural capacity for extended durations when exposed to fire" (p. 290). The

second reason is that like concrete slabs and solid wall panels CLT panels avoid concealed spaces which limits the spread of fire. The third reason is that CLT is typically used for floors and walls which allows fire-rated compartmentalization ("The CLT Handbook" 2013).

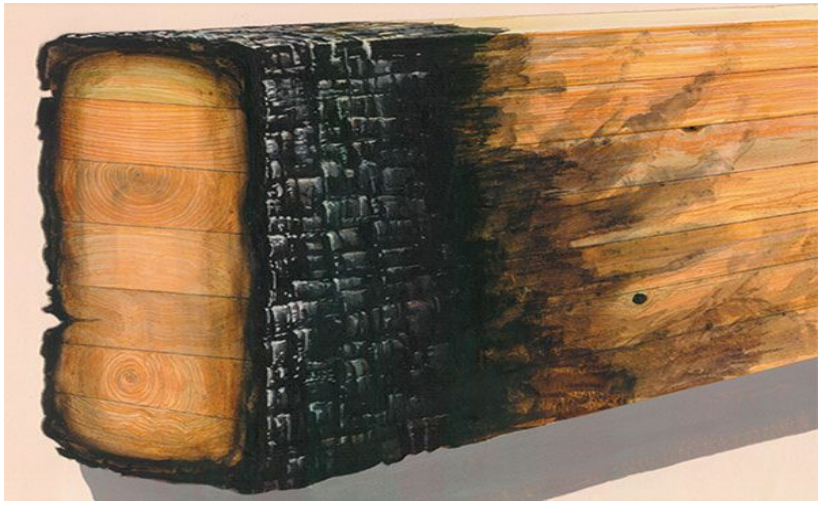

Figure 2. A photo of a charred engineered wood product. Retrieved from https://www.pinterest.co.uk/pin/421297740124892547/.

CLT floors and walls have a sizable chance of providing sufficient sound insulation with the proper design ("The CLT Handbook" 2013). It is shown that mass is one important factor in determining how well CLT floors and walls stand up to sound insulation performance. If the question of whether wood structures fare well against earthquakes arises, the answer is that they generally do. According to Schneider et al. (2014), "This is achieved through a high strength-to-weight ratio of wood, structural redundancy, and energy dissipation capacity" (p. 1).

One of the most crucial benefits of CLT is its environmental performance. Photosynthesis allows trees to store carbon from carbon dioxide. There is a lot of discussion about carbon sequestration in CLT and it is largely true due to the fact that there is value in that stored carbon. The value can be seen as the wood keeping the carbon from going into the atmosphere. The CLT Handbook (2013) states that "In total, the wood content of the modeled CLT building equates to

about 951 metric tons of CO_2. To put this amount in context, 951 metric tons of CO_2 are emitted in one year of driving 186 cars" (p. 454).

Along with the combustibility issue, others might raise the question about how cutting down trees to use in timber construction is not exactly a sustainable practice. This is a valid concern, however, sustainable forest management practices in North America keep forests from becoming depleted. According to the CLT Handbook (2013), "Since 1952, the growth-removal ratios for both softwood and hardwood demonstrate that growth has exceeded harvest and the United States has not been depleting its forest resources from a timber volume standpoint, even during periods of high demand" (p. 458). Another bonus of CLT is that it can utilize lumber that has been ravaged by insects and disease which would otherwise be a wasted resource if the trees were left standing. Forest that are in danger of deforestation and illegal logging are occurring in uncertified forests located in developing countries where sustainable forest management is not properly managed. "As of August 2012, more than 500 million acres of forest in Canada and the United States were certified under one of the four internationally recognized programs used in North America…accounting for approximately 29% of North American forests" ("The CLT Handbook", 2013, p. 460).

There are other reasons why wood is a more sustainable material than steel and concrete. Unlike steel and concrete, CLT is a renewable material. CLT has a negligible impact on indoor air quality which may contribute to well-being in humans. CLT has a great chance for reusability which could greatly decrease the waste in deconstruction of buildings. In terms of energy savings, CLT contains thermal mass. "…Thermal mass is often identified as a contributor to overall savings in a building's heating and cooling loads…" ("The CLT Handbook", 2013, p. 462).

2.3 METHODS OF FABRICATING CLT

There is a myriad of different methods to fabricate CLT panels (see Figure 3). Generally, CLT is manufactured by selecting boards, producing finger jointed lamellas, and then single layer

panels (Brandner et al. 2016). After production of single layer panels, the next steps are adhesive application, pressing of boards, and the finishing touches. Generally, softwood is used in the construction of CLT as opposed to hardwood; the softwood species, Norway spruce (*Picea abies*), is typically used in European CLT production (Brandner et al. 2016). Local species of trees can be used in CLT production which would be beneficial so that shipping does not figure into the cost of making the CLT. However, Brandner et al. (2016) states that local species are of a "…lower mechanical quality than Norway spruce" (p. 335).

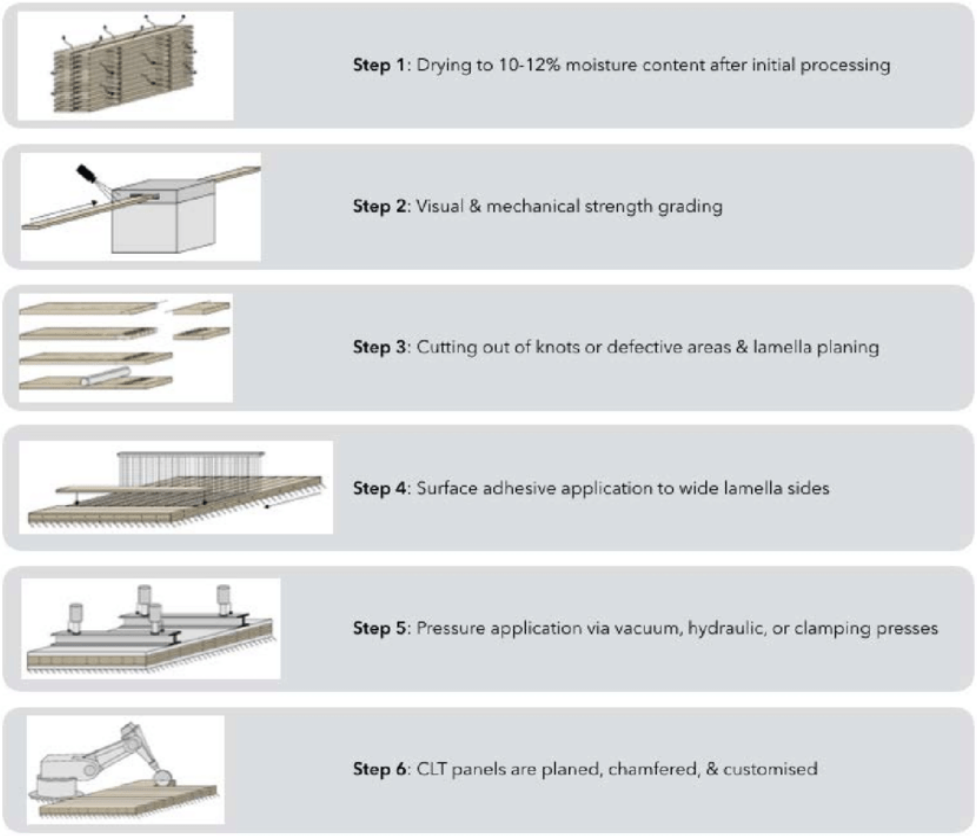

Figure 3. CLT Fabrication Process. Retrieved from https://www.researchgate.net/figure/2-CLT-manufacturing-process-Source-Own-elaboration-adapted-from-Brettsperrholzorg_fig7_321748256.

One study on cross-laminated timber tested hybrid CLT in terms of its lateral and withdrawal capacity for fasteners. Hybrid CLT is known as CLT with different layers of tree species/grades, and they produced CLT panels in three- or five-layers using phenol-resorcinol

formaldehyde adhesive with an applied pressure of 0.7 MPa. There were several different tree species that were used and in different combinations such as Douglas fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and western hemlock (*Tsuga heterophylla*). The wood was visually graded and the low-grade was used in the inside of the CLT panels while the high-grade material was used on the exterior faces and in the core layer of reference panels. Then, the lumber was planed to make sure that the layers bonded strongly, the adhesive was applied, and the layers were pressed together. The results showed that douglas fir had higher yield load values because it had a higher specific gravity than lodgepole pine (Vahid et al. 2018).

Another study on CLT tested the bending and compressive properties of CLT made from Canadian hemlock. This study used 20 5-meter long CLT panels with 5 layers and made them using polyurethane adhesive with an applied pressure of around 800 kPa. The authors measured the bending performance in the major strength and minor strength direction. The bending properties of Canadian hemlock were compared to that of CLT made from spruce-pine-fir or douglas fir-larch. The results showed that the strength and stiffness of Canadian hemlock was much greater parallel to the major strength direction compared to regular CLT panels (He et al. 2018). In comparison to the previous study by Vahid et al., this study showed that Canadian hemlock is a promising candidate for CLT whereas the previous study showed that hybrid CLT made from Douglas fir would outperform other species. Contrasting the two studies, they had two different methods of producing CLT in terms of the length of the boards, the adhesive used, and the pressure used, and this is a determining factor of which tree species would be the one to have the highest strength.

2.4 CONNECTIONS IN CLT

Connections in CLT are integral to the design of the structure. There are several different kinds of connections such as nails, screws, bolts, lag bolt or lag screws, and split ring and shear plate connectors. The National Design Specification handbook (2018) uses the yield limit model for

dowel-type fasteners in the design of laterally loaded connections. Dowel-type fasteners are just fasteners with a generally cylindrical shape. Laterally loaded connections are also known as shear connections which are connections that "…have the load applied perpendicular to the length of the fastener" (Breyer et al., 2015, p. 628). On the other hand, withdrawal loading is when the load is applied "…parallel to the length of the fastener and the fastener is loaded in tension…" (Breyer et al., 2015, p. 630). The yield limit model uses connection geometry and material properties to measure strength. The factors used to calculate the basic load capacity of a fastener include fastener diameter, dowel bearing length, fastener bending yield strength, dowel bearing strength of wood member, and, in the case of metal plates or concrete embedment, the dowel bearing strength of the metal or concrete. "The bending yield strength of the fastener F_{yb} is a property that is used to predict the load capacity of a mechanism that involves the formation of a plastic hinge in the fastener" (Breyer et al., 2015, p. 636). The dowel bearing strength is the property of strength of the elements in a connection that resists embedding of a dowel (Breyer et al. 2015). This paper will discuss in further detail four specific fasteners/connections: nails, screws, bolts, and splines.

2.4.1 Nails

The National Design Specification handbook (2018) gives guidelines on different kinds of nails including common nails (see Figure 4) & spikes, box nails, sinker nails, threaded hardened-steel nails, post-frame ring shank nails. "Common, box, and sinker nails are all fabricated from low-carbon steel wire with a plain shank and a diamond point" (Breyer et al., 2015, p. 657). Meanwhile, threaded nails are made of high-carbon steel wire, have a helically or annularly threaded shank, a flat head, and a diamond point. The yield limit equations for a nail in single shear have many variables and cover a variety of failure modes (Breyer et al. 2015). Ringhofer et al. conducted a study on design approaches of dowel-type fasteners. In this study, different dowel-type fasteners including profiled nails, smooth dowels and tight-fitting bolts, and self-tapping screws were used (2018). The

results of this study provided evidence that profiled nails should be used for axial and lateral loads on the side face of CLT and should not be used for any loads on the narrow face of CLT (Ringhofer et al. 2018). Meanwhile, in the study by Vahid et al. the results showed that nails did not have a higher yield load than wood screws (2018). This was also true for withdrawal loading due to the fact that the nails had lower values for withdrawal strength than screws (Vahid et al. 2018).

Figure 4. 8/9/11 Gauge Decking nails. Retrieved from http://www.jaaco.com/premium/.

2.4.2 Screws

There are several different types of screws (see Figure 5) that are used in CLT construction which are lag screws, wood screws, and self-tapping screws. Wood screws according to Breyer et al. (2015) are "…similar to lag bolts but are smaller in diameter, have a slightly tapered shank, and do not have a hex (or square) bolt head" (p. 632). These kinds of screws have larger adjusted design values for lateral and withdrawal load compared to nails (Breyer et al. 2015). Wood screws are used

more widely in Europe and have some application in manufactured housing ("The CLT Handbook" 2013). There was a study that was performed by Loss et al. that studied shear connections with spatially arranged screws (2018). The study used simple butt joints with crossed self-tapping screws and studied the impact of reversed-cyclic and quasi-static monotonic loading (Loss et al 2018). The authors tested connection yield load, elastic stiffness, ductility, and load-carrying capacity and related slips (Loss et al 2018). Loss et al. (2018) states "In particular, performance can be changed merely by changing the screw angle with respect to the loading direction, as well as varying the screw length and related threaded portion length. In general, configurations that maximize the elastic stiffness reduce the screw's capacity in deformation and ductility" (p. 354). Screw angle determined stiffness, ductility, and energy dissipation (Loss et al 2018). Ringhofer et al. stated in their study that self-tapping screws can be used for axial and lateral loads for both the side and narrow face (2018).

Figure 5. 316 Stainless Steel Deck screws. Retrieved from https://lightningboltandsupply.com/316-stainless-steel-deck-screws.html.

2.4.3 Bolts

A bolt (see Figure 6) is normally used for larger loads and the angle of load to grain is a major factor in the design of large-diameter fasteners. According to Breyer et al. (2015) "Most bolts are used in laterally loaded dowel-type connections…For example, the most common connections are either single-shear or double-shear joints…Connections can be wood-to-wood or wood-to-metal" (p. 728). Values for the reference design value, Z, are determined by the following conditions: load parallel to grain in both main member and side member, load perpendicular to grain in side member and parallel to grain in main member, load perpendicular to grain in main member and parallel to grain in side member, and load perpendicular to grain in both main member and side member (Breyer et al. 2015). According to Ringhofer et al., tight-fitting bolts should only be used for lateral loads on the side face of CLT and is not applicable on the narrow face of CLT (Ringhofer et al. 2018).

Figure 6. Different sizes of steel hex bolts and washers. Retrieved from https://www.aliexpress.com/item/32801600226.html.

2.4.4 Splines

According to the CLT Handbook, a spline is a strip of lumber usually made out of plywood, laminated veneer lumber, parallel strand lumber, or laminated strand lumber (2013). In this specific project, single surface splines will be used (see Figure 7). Single surface splines are usually configured to fit into a wood assembly by making notches at the corners of the CLT panel and placing the spline into the space that the notches create. Fasteners such as nails and screws or adhesive are then used to connect the spline to the CLT panels.

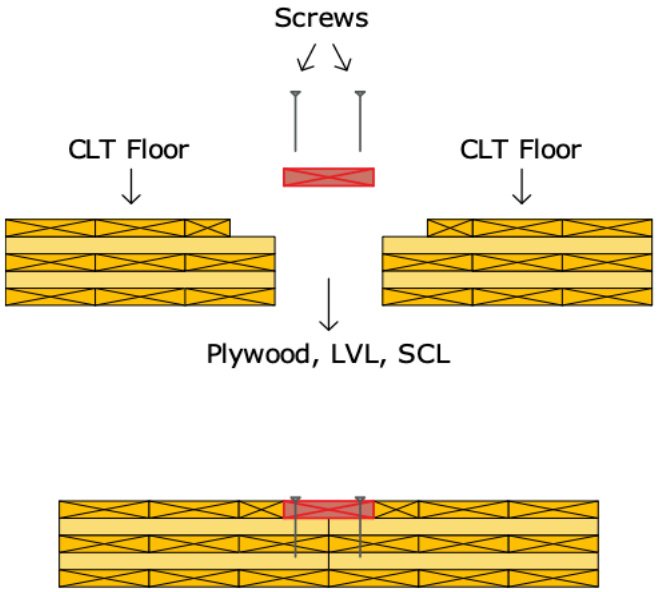

Figure 7. Single surface splines. Taken from: Karacabeyli, E., and Douglas, B. (Eds.). (2013). The CLT Handbook. FPInnovations and Binational Softwood Lumber Council.

Different studies have performed tests on single surface spline configurations of CLT. One such study done by Sullivan et al. looked at monotonic and cyclic tests to test the strength and stiffness characteristics of several different shear connections. One of their test specimens (see Figure 8) included three CLT panels connected together by two splines and the splines were

fastened onto the CLT panels with self-tapping screws staggered in adjacent rows (Sullivan et al., 2018).This was the inspiration for the specimens in this project due to the fact that this CLT and spline configuration could offset the rotational effects of lateral loading on one shear plane if properly set up in the testing machine. However, the test apparatus used in Sullivan et al.'s project is rather different than the one in this project. The test apparatus that Sullivan et al. used consisted of a horizontal loading table that could perform monotonic and cyclic tests. The key aspect of this configuration is that the CLT panels at the two ends are fastened down with steel pipes while the middle CLT panel is connected to the machine which will perform the loading (Sullivan et al., 2018). In this project, we will be using a vertical loading machine.

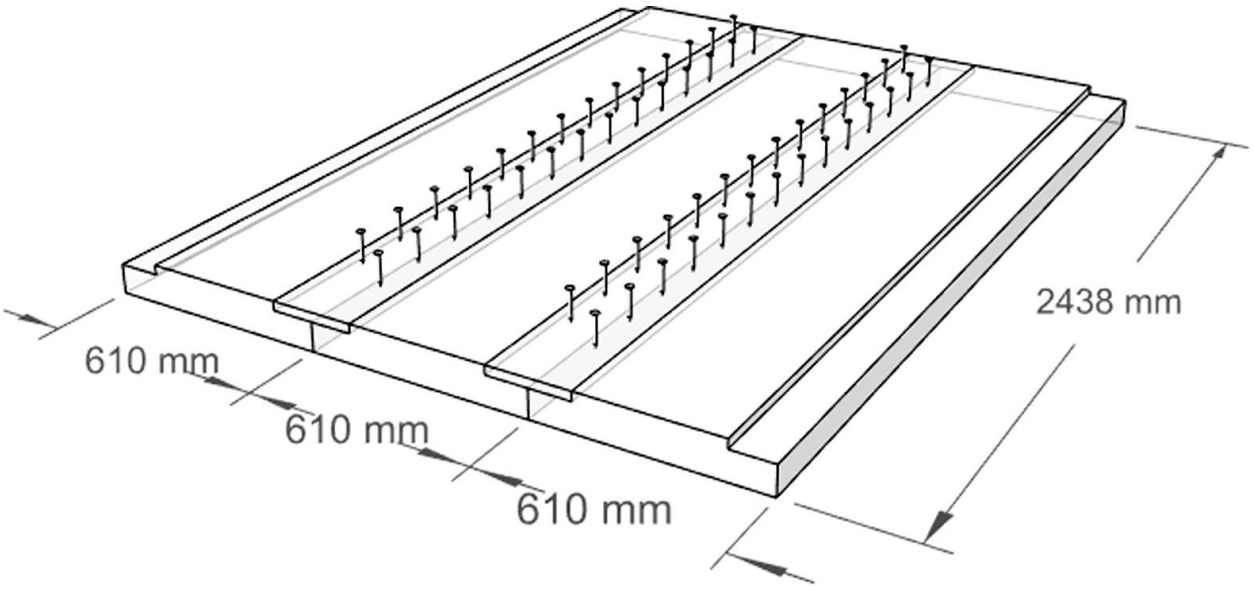

Figure 8. Three CLT panels connected together with two splines – Diagonal View. Taken from: Sullivan, K., Miller, T. H., & Gupta, R. (2018). Behavior of cross-laminated timber diaphragm connections with self-tapping screws. Engineering Structures, 168, 505–524. https://doi.org/10.1016/j.engstruct.2018.04.094

2.5 STRUCTURAL SYSTEMS OF CLT

Mechanical connections/ fasteners can connect CLT in a variety of structural connection systems. This paper will discuss connection systems that are panel-to-panel, wall-to-wall, and wall-to-floor.

When it comes to panel-to-panel connections, the connection system must resist in-plane shear and out-of-plane bending in wall assemblies. The CLT Handbook (2013) states that "When the connection is used in floor assemblies acting as diaphragms, however, the connection must be capable of transferring in-plane diaphragm forces in principle and maintain the integrity of the diaphragms and the overall, lateral load resisting system" (p. 191). One panel-to-panel connection system is internal splines where single or double wooden strips made out of laminated veneer lumber, thin CLT, or plywood are used to put two panels together. Mechanical fasteners like screws may be applied to the system to make it stable. Single surface splines use a strip of lumber and screws to connect two CLT panels at the surface. This connection does not perform as well as an internal spline connection. Double surface splines use two strips of lumber and screws to connect CLT panels on its exterior surface. These are generally better than single surface splines in terms of strength and stiffness but may take longer to make ("The CLT Handbook" 2013).

For wall-to-wall connections, there are three additional connection details that can be used which are wooden profiles, metal brackets, and concealed metal plates. Connections using wooden profiles to connect a wall to another wall usually includes the used of self-tapping screws. These little wooden profiles which are also called keys provide more stability to the connection. L-shaped metal brackets are also used in wall-to-wall construction along with screws or nails. According to the CLT Handbook (2013), "This connection system is one of the simplest and most efficient types of connection in terms of strength resulting from fastening in the direction perpendicular to the plane of the panels or recessed" (p. 197). The metal also adds a membrane of fire resistance. Concealed

metal plates can also make up a wall-to-wall connection system. Although it provides advantages in terms of strength and stiffness, "…the system requires precise profiling at the plant…" ("The CLT Handbook", 2013, p. 198).

Wall-to-floor connection systems feature the same mechanical fasteners to connect them as wall-to-wall connection systems. These connection systems use self-tapping screws, metal brackets, and concealed metal plates. Balloon construction is also used in wall-to-floor connection systems. It is generally "…a type of structural system where the walls continue for a few stories with intermediate floor assemblies attached to those walls" ("The CLT Handbook", 2013, p. 186).

2.6 CONCLUSION

All in all, CLT has proven to be an excellent alternative to concrete and steel for construction materials. This is due to its strength, stiffness, floor vibration performance, sound insulation performance, fire performance, seismic performance and last but not least its environmental performance. Connections in CLT have also proven to be important to build wood structures since without the support and stability that they give wooden structures would be in poor condition. Nails are the simplest and most popular mechanical connection for lighter loads while screws and bolts are used mostly for heavier loads. Timber construction is gaining popularity due to the appearance of CLT, glulam, and other engineered woods. The advantages of CLT outweigh the disadvantages and its sustainable nature has put it on the market to save our buildings from being aggravators of climate change.

3 EXPLANATION OF CURRENT METHODOLOGY AND GOALS

3.1 MATERIALS

The materials used in this project mainly consisted of Eastern Hemlock cross laminated timber, birch plywood, polymer coated exterior screws, premium construction adhesive, shop tools and machines, laminated veneer lumber, steel rods, coupling nuts, and angled plates. A more detailed list of the tools and materials used in this project can be found in the Appendix.

3.2 METHODS

3.2.1 CLT Specimens

The specimen that ended up being developed for this project (see Figure 9) consisted of three panels of cross laminated timber connected with plywood splines (e.g. strips of wood) that were screwed into the CLT.

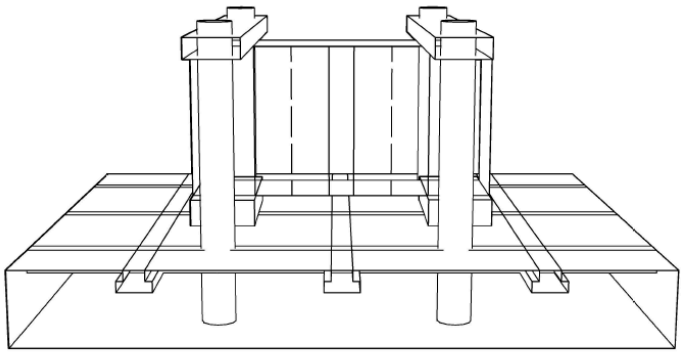

Figure 9. Early AutoCAD model of specimen and experimental test set-up.

The independent variable that we controlled was whether or not adhesive was applied underneath the splines. In order to make the specimen, panels of Eastern Hemlock cross laminated timber were found amongst a pile of wood that were previously used for other experiments. They were sorted into usable and non-usable piles. Most of the usable pieces of cross laminated timber were still broken in places but were salvageable enough to use in this project (see Figure 10).

Figure 10. Stack of CLT panels on a cart.

Once all the pieces were sorted, they were kept in the conditioning chamber to achieve the desired moisture content of 12%. They were kept there for approximately a month before fabrication of the specimens began so that equilibrium was attained.

The first step in fabricating the specimen was to take the panels of Eastern Hemlock CLT and measure 6 inches off the edge to get a 4 in. x 6 in. x 12 in. Eastern Hemlock CLT block (see Figure 11). The piece of wood was placed on the chop saw and cut down to the appropriate size.

Figure 11. Cutting down CLT panel to 4 in. x 6 in. x 12 in. CLT block.

Once all the panels were measured and cut, they were further divided using the band saw. In short, the 4 in. x 6 in. x 12 in. CLT block became three 4 in. x 6 in. x 4 in. CLT cutoffs (see Figure 12). The band saw was set up to cut 4 in. cutoffs and the CLT blocks were passed through the band saw.

Figure 12. Cutting down CLT block into 4 in. x 6 in. x 4 in. CLT cutoffs.

Afterwards, the plywood arrived and was cut into a more manageable size by the panel saw. This half sheet of plywood was cut down into 3-inch panels by the table saw. These were cut further into ¾ in. x 3 in. x 6 in. pieces (see Figure 13) by the chop saw to become the splines for the project.

Figure 13. Stack of plywood splines.

Further, the notches in the CLT cutoffs needed to be made in order for the splines to fit and connect two CLT cutoffs. The table saw was used along with dado stacks to cut the notches into the CLT cutoffs (see Figure 14).

Figure 14. CLT specimen with notches and leftover strips of wood.

Not only did the Eastern Hemlock contain numerous knots but stress cracks were also present because they were used in previous experiments. This made cutting the notches into the CLT cutoffs a difficult and dangerous task. Some CLT cutoffs were disposed of due to the fact that they could easily be broken. The project initially planned to test 40 specimens but ended up testing 36 because of this. After the notches were cut into the CLT cutoffs, there was still some wood left that needed to be chiseled off to keep the notch uniform and level throughout (see Figure 15).

Figure 15. Chiseling off strip of wood from notch.

The next phase of the experiment consisted of drilling screws to connect the splines to the CLT and applying adhesive to half of the specimens. In order to be precise about where the screws were placed, a ruler was used to measure where the screws would go. This, however, was particularly inefficient especially in terms of time so a new method to place where the screws would go was devised (see Figure 16). A scrap piece of plywood was measured with a ruler and marked with a pencil to show where the screws would go. Then holes were drilled in the marked spots. This was so that the scrap piece of plywood could be clamped onto a spline and an awl could be inserted into the hole. A rubber mallet was then used to hit the awl so that it could punch a small hole in the spline to show where the screw would go. This method was performed on a majority of the splines.

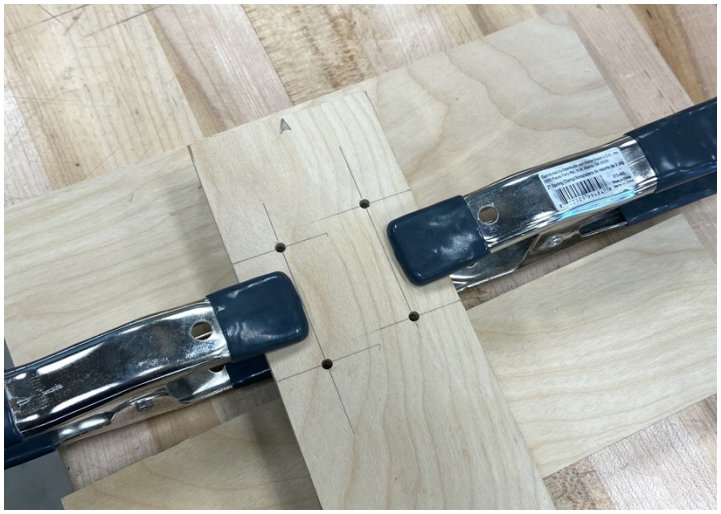

Figure 16. Screw placement process.

After this was performed, the splines were placed in the notches and connected to the CLT cutoffs using screws. First, the CLT cutoffs were placed right next to each other to form a specimen and the specimen itself was clamped together to avoid movement. Second, the clamped specimen was clamped down onto the table along with one of the splines. Then, a cordless impact driver was used to drill in the screws one by one. This process was repeated for the second spline. This was done until all the splines were drilled into the notches in each specimen (see Figure 17).

Figure 17. Drilling screws to connect splines and CLT panels.

For the specimens that required adhesive, the initial step was to place the construction adhesive in a caulking gun. The caulking gun was used to place the adhesive onto the notches. Then, a popsicle stick was used to spread the adhesive on the notch (see Figure 18). Furthermore, the spline was placed on the adhesive and clamped down. Finally, the screws were drilled in place all while making sure the spline did not move about because of the adhesive.

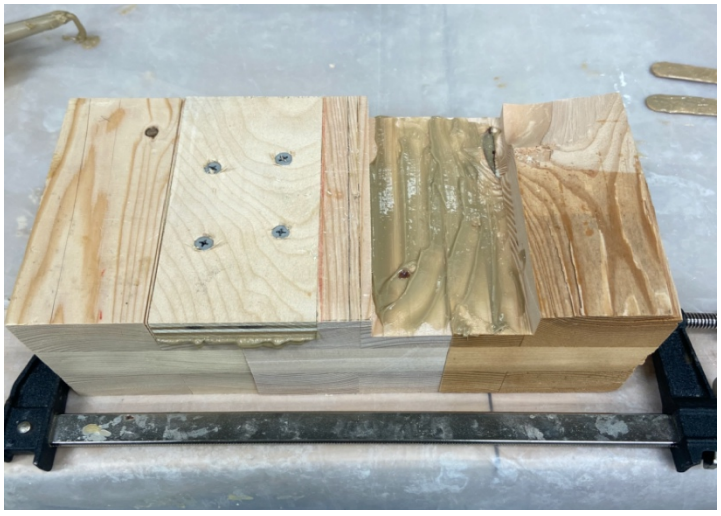

Figure 18. Applying adhesive to notches.

3.2.2 Experimental Test Set-Up

In order to allow monotonic and cyclic loads to be applied to the specimen, a set-up needed to be constructed to allow this to happen. This experimental test set-up was developed by my thesis advisor, Dr. Peggi Clouston, and Wood Shop manager, Evan Janes. Two panels of laminated veneer lumber (LVL) were taken from a wood pile and used to hold down the specimens during cyclic testing. These LVL panels were cut down to ¾ in. x 19 in. x 2 in. Then, a 3/8" hole was drilled into the two ends of the LVL panels. Steel threaded rods, coupling nuts, and T-slot nuts were bought. These were assembled so that the bottom end of the threaded rods would have the T-slot nuts and the threaded rod could be slid into the T-slot table. Since the threaded rod was too short, two threaded rods were connected together using coupling nuts so that they could be inserted through the LVL panels. The LVL panels were placed through the threaded rod and washers were placed on the top of the holes. Nuts were threaded onto the rod right above the washers so the specimen could be tightened down using a wrench.

Another part of the experimental test set-up involved crafting the component that would allow for the inner CLT cutoff to move in tension (see Figure 19). This component was crafted using two angled steel plates that were connected together with a flat rectangular steel plate.

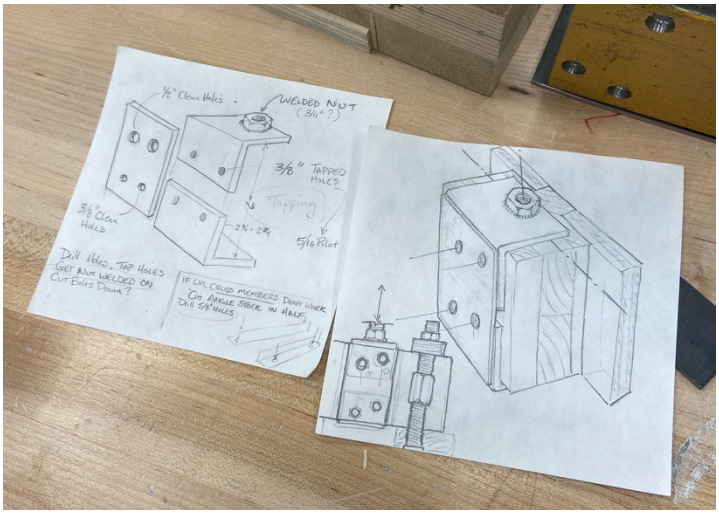

Figure 19. Conceptual sketches of the apparatus (Courtesy of Evan Janes).

The first task in crafting this apparatus was to weld a ¾ inch nut onto the top of one the angled plates. This was so that we could attach the load cell of the MTS testing machine to it in order to apply the loads on the specimen. In order to attach the angled plates onto the flat plate, two holes had to be drilled and tapped on each angled plate. They were originally holes on the plate but they were not fit to be used since they were not of the right size and were not tapped. The sides of the angled plates that had the holes were the ones that were drilled into because the other side needed to be free of obstructions in order to weld the nut. All four holes were 3/8 inch but the four holes in the flat plate were different so that the apparatus could adjust to the size of each specimen. The top two holes on the flat plate were ½ inch and the bottom two holes were 3/8 inch. The holes in the flat plate were drilled as well and then 3/8-inch button head hex drive screws were bought and threaded into the holes. This transformed the three plates – two angled plates and one flat plate – into one singular unit. This apparatus was attached to the load cell of the MTS testing machine and each specimen was placed into it (see Figures 20 – 22). The apparatus was adjusted accordingly by tightening the button head hex drive screws with an Allen key. The experimental set up continued accordingly by placing blocks of steel on top of the T-slot table to support the specimen. The LVL panels connected to the steel rods were moved into place to hold the specimen down. The nuts on top of the LVL panels were hand tightened and then a wrench was used to make sure the panels had a very firm hold on the specimen. After this was done, aluminum plates were placed in the gap between the angled plate and the top of the specimen to make sure the plate apparatus had a very tight fit on the specimen. Once the nuts are tightened and the aluminum plates are firmly inside the gap, then testing can begin.

Figure 20. Front view of experimental test set-up.

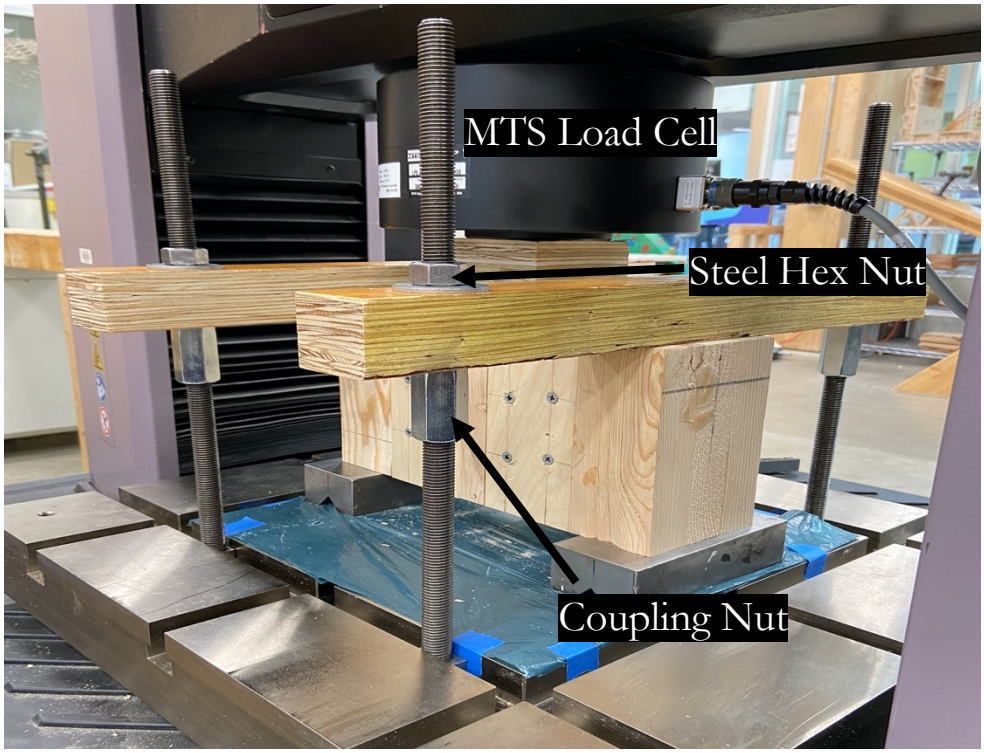

Figure 21. Right side view of experimental test set-up.

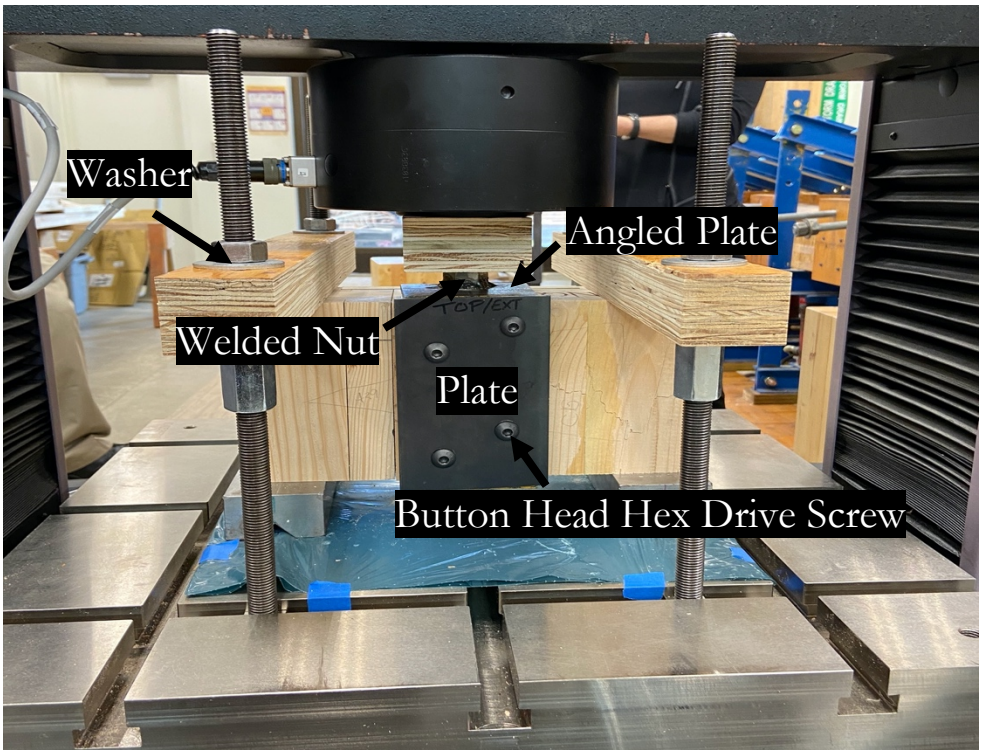

Figure 22. Back view of experimental test set-up.

3 REPORT AND DISCUSSION OF RESULTS

Nine of the non-glued and nine of the glued specimens were tested under monotonic compressive loading. Each specimen was loaded in compression at a speed of 0.1 in/min. Meanwhile, nine of the non-glued and nine of the glued specimens were tested under cyclic loading. Each specimen was tested at a rate of 0.2 in/min. Graphical summaries of all nine tests for each of the four treatments can be found in Appendix B. When testing the cyclic specimens, the cycle was initially supposed to run from a displacement of -0.27 inches to 0.27 inches. However, the flat steel plate that was connected to the angled plates in the apparatus was bending. This caused the graph to incorrectly present the load and displacement. The decision was made to just let the cycle go from 0 inches to 0.27 inches so that the data could be presented correctly.

The results are graphically presented in Fig. 23 – 26. The graphs show a continuation of each treatment which presents one trial which was run longer than the others. This was done to determine what the behavior of the assembly would be under those conditions. In Figure 23, the graph shows that both the non-glued monotonic and the non-glued cyclic responded similarly. This means that there is not much difference in the behavior of non-glued specimens whether they are tested under monotonic or cyclic loading. In other words, they deteriorate in a similar way under both treatments. In Figure 24, the graph shows that the glued specimens were able to withstand higher loads than the non-glued specimens under monotonic loading. This can be supported in Table 2 where the percent difference between the yield points of both treatments was 70.39%. In Figure 25, the graph shows that the glued specimens were able to withstand higher loads than the non-glued specimens under cyclic loading similar to Figure 24. This can be supported in Table 2 where the percent difference between the yield points of both treatments was 67.17%. In Figure 26, the graph shows that the glued specimens under cyclic loading were able to bear higher loads than under monotonic loading. The cyclic nature of the loading affords the glued specimens time to

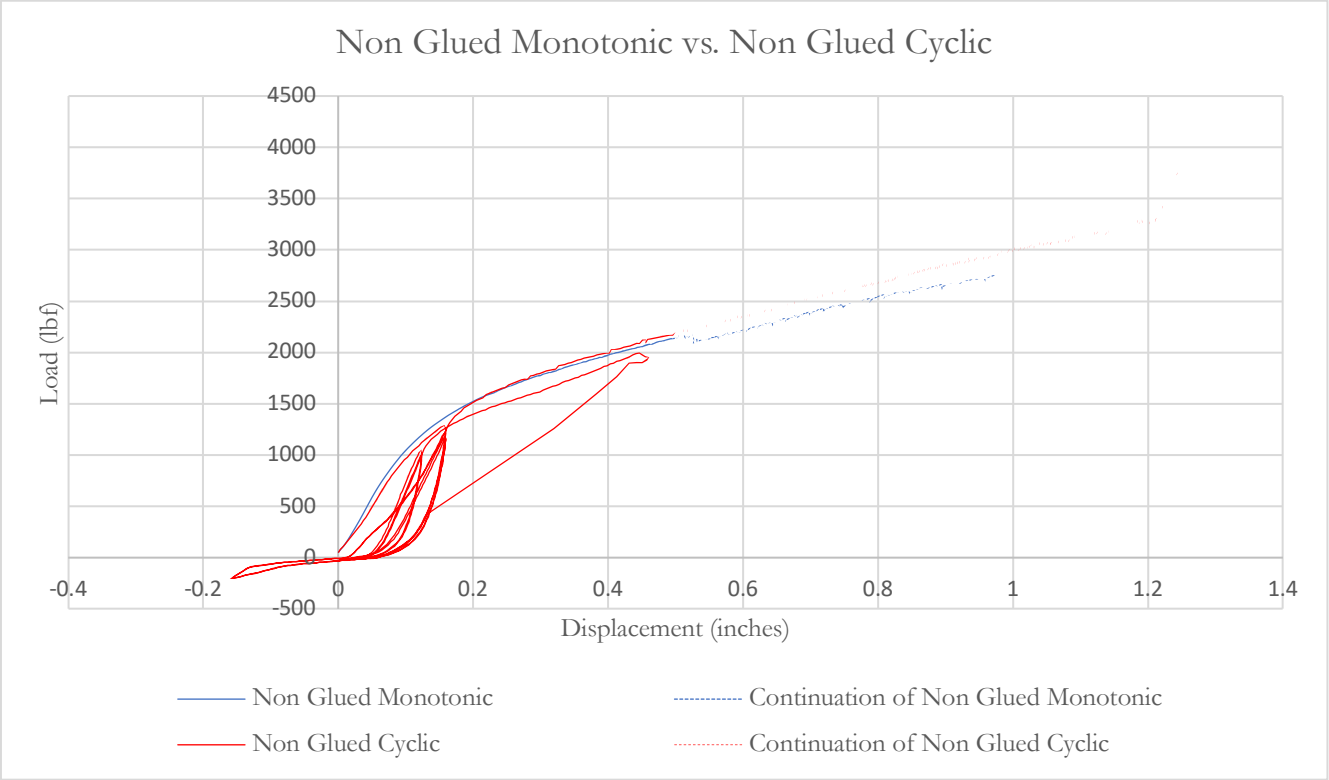

Figure 23. Average Load and Displacement for NGM vs. NGC specimens

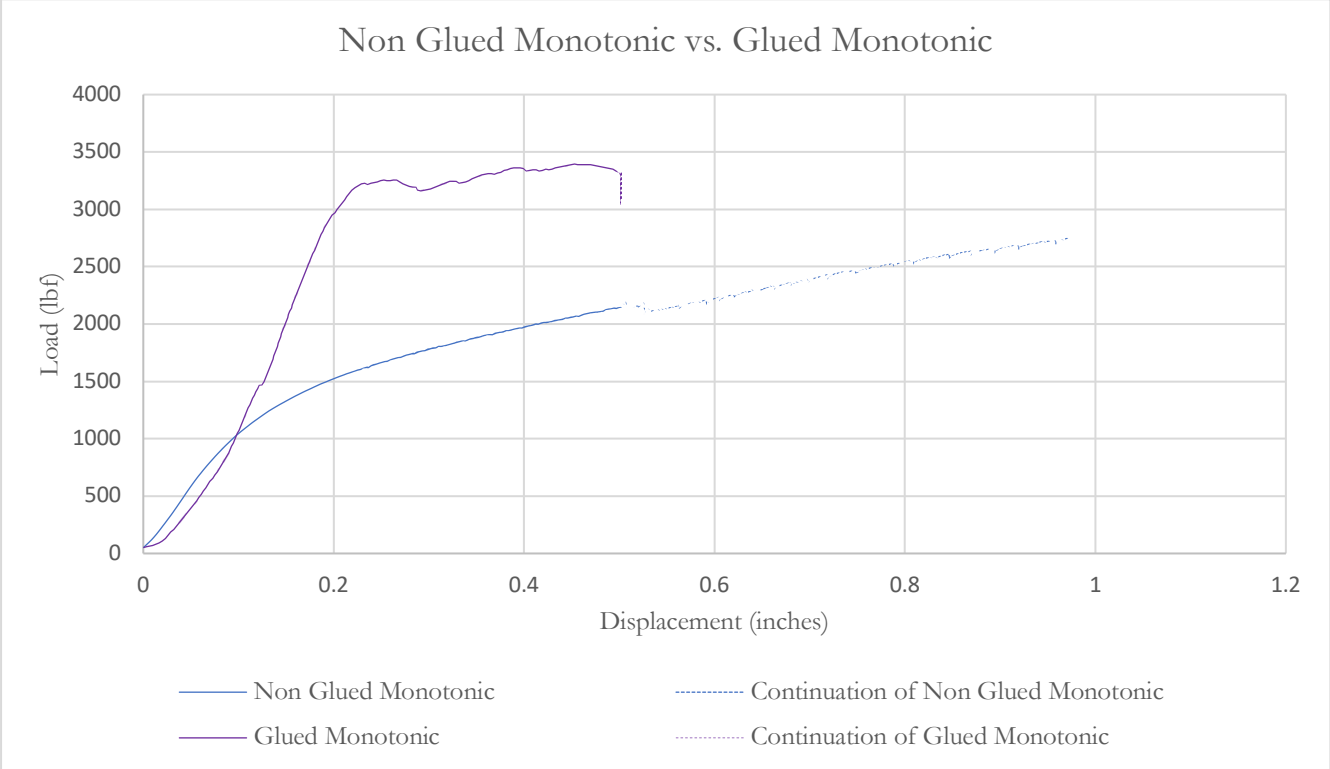

Figure 24. Average Load and Displacement for NGM vs. GM specimens

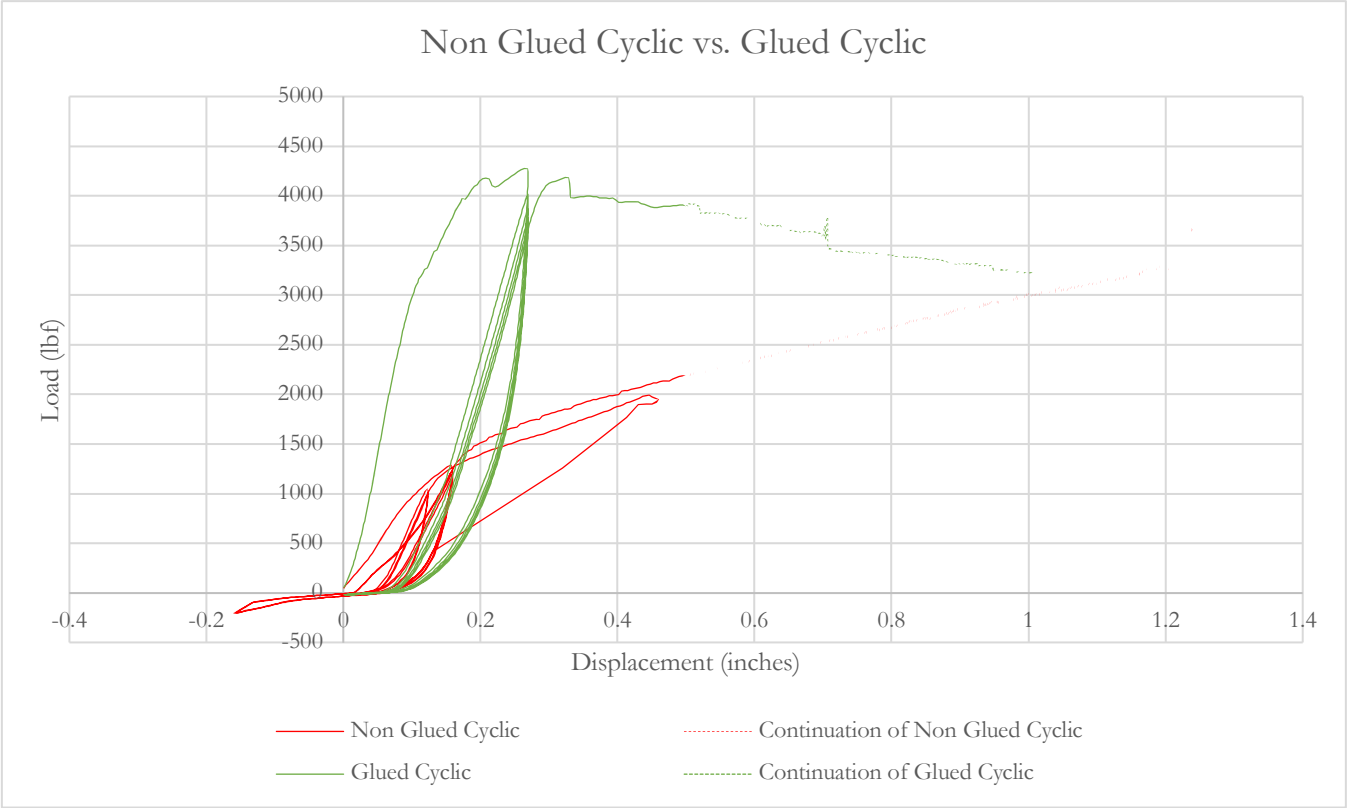

Figure 25. Average Load and Displacement for NGC vs. GC specimens

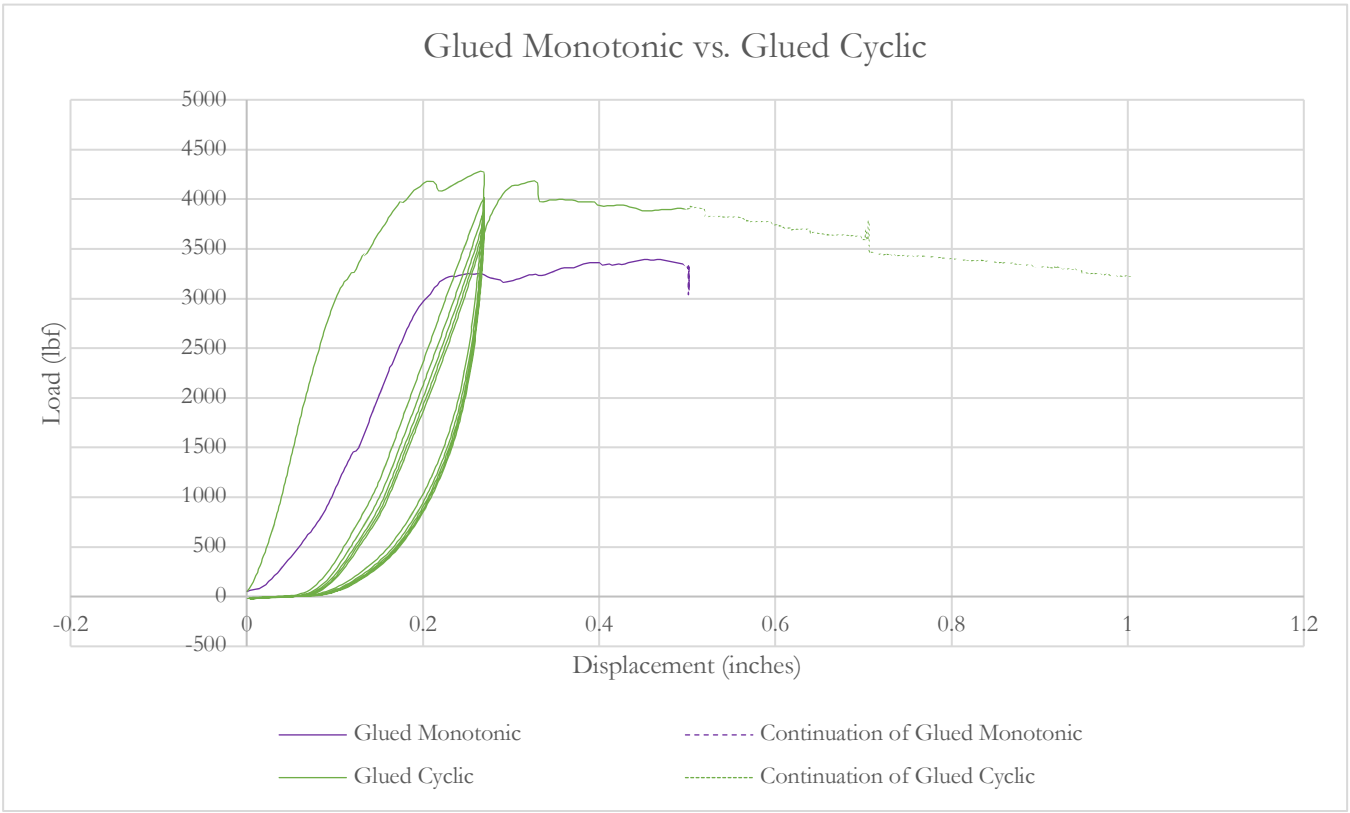

Figure 26. Average Load and Displacement for GM vs. GC specimens

revert back to their original shape when the loading goes into tension whereas the monotonic glued specimens were continuously being compressed. The continuous nature of the loading did not allow the monotonic glued specimens to be able to bounce back to their original undeformed state. This is different in comparison to the non-glued monotonic and cyclic specimens which behaved similarly. Since there was no adhesive to create a stronger bond in the connection, the different types of loading would not impact the deterioration of the specimens as much as the glued ones.

Table 1 summarizes the percent differences between yield points for the four treatments. The highest percent difference is between the glued monotonic and the non-glued monotonic which illustrates that specimens perform the poorest without adhesive under continuous loading whereas when adhesive is applied the specimens perform much better. It should also be considered that the glued specimens perform the best under cyclic loading, but this is also true for the non-glued specimens which explains why their percent difference is less than the non-glued vs. the glued monotonic specimens. Overall, the adhesive creates the greatest difference in performance when subjected to monotonic loading. The two percent differences that compare both loadings under each condition (e.g. non-glued or glued) show that there was less of a difference in specimen response within each type of specimen. In other words, there was less of a variability among non-glued or glued specimens when subjected to two different types of loadings.

Table 1. Percent difference between different treatments

	Yield Point (lbf)		**Percent Difference**
NGC vs. NGM	1292	900	30.34%
GC vs. GM	3935	3040	22.74%
GM vs. NGM	3040	900	70.39%
GC vs. NGC	3935	1292	67.17%

Table 2. Yield point, displacement yield point, and COV for different treatments

Treatment	Yield Point (lbf)	Displacement Yield Point (in)	Coefficient of Variation
NGM	900.0	0.0817	32.1%
NGC	1292	0.1580	121.3%
GM	3040	0.2060	47.1%
GC	3935	0.1664	96.3%

Yield point and displacement yield point were calculated from data from each treatment (see Table 2). These two values were computed by finding the 0.5% offset line from the initial linear part of the graph. According to ASTM D5764 – 97a, the standard for embedment strength, it is suggested that the offset line should be 5% of bolt diameter. Originally, the yield point for the non-glued and glued monotonic treatments were determined at approximately 4% offset. These yield points were used in the cyclic tests to determine the maximum displacement the test cycle should reach. However, pushing the curve further into yield state before reversing the load helped better show specimen deterioration.

5 CONCLUSIONS AND IMPLICATION FOR FUTURE RESEARCH

The goal of this research was to quantify the behavior of glued and non-glued panel to panel assemblies of single surface splines subjected to both monotonic and cyclic loading. The specimens were comprised of three CLT panels connected together with two splines of plywood. They were fabricated by cutting the wood into the desired length using shop tools, creating notches, drilling screws to connect the plywood and the splines, and adding adhesive to the notches for the glued specimens. Nine series of tests were completed for each treatment:

- Non-glued monotonic testing (NGM)
- Non-glued cyclic testing (NGC)
- Glued monotonic testing (GM)
- Glued cyclic testing (GC)

Experimental results for each of the tests were compared and conclusions were drawn. Through the testing process, it was found that panel to panel assemblies of single surface splines withstood higher loads when adhesive was applied to the notches. Therefore, they performed stronger and stiffer than the assemblies without adhesive which supports my hypothesis. The glued specimens subjected to cyclic testing had a graph that was above the graphs for all other treatments meaning that when connections are subject to cyclic loads they will fare better when there is adhesive. The glued specimens under monotonic testing although lower than the graph for glued specimens under cyclic testing was also higher than both the monotonic and cyclic testing for non-glued specimens. While glued connections may perform stronger and stiffer, there is still some variability in the tests that were performed as the various graphs for each test did not line up with one another. This could mean that glued specimens respond differently in slightly different conditions or that the specimens which were compromised (e.g. cracks, gaps, etc.) from the start could have contributed to the variability. Although the non-glued specimens did not withstand higher loads than the glued

specimens, the response between the specimens that received both monotonic and cyclic loading was not all that different because their graphs aligned well with each other. The only notable difference is that the non-glued specimens that went under cyclic loading bore slightly higher loads than the ones that underwent monotonic loading.

Overall, this research shows that when CLT panel to panel assemblies of single surface splines include adhesive, they will perform stronger and stiffer but with more variability. Further investigation of this study can be expanded upon in the future by considering other wood species, other CLT configurations (larger lamstock like 2 x 6's or 2 x 8's), and other fasteners. Also, to improve upon the work in this project, one could use CLT specimens that are not previously stressed. The fabrication process should ensure that, although wood is naturally highly variable, the specimens be as similar as possible to each other. Another point that could be explored is using different yield point offsets in order to vary levels of damage when cycling load. In addition to this, the creation of a fixture that could ensure that cyclic testing could be performed into the reverse loading range, would provide more insight. The types of loading and the number of tests that could also be increased in a future project to lead to research advancement.

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Figure 3-2. CLT manufacturing process Source: Own elaboration adapted... (n.d.). Retrieved December 11, 2019, from ResearchGate website: https://www.researchgate.net/figure/2-CLT-manufacturing-process-Source-Own-elaboration-adapted-from-Brettsperrholzorg_fig7_321748256

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Many, many thanks to Evan Janes for helping me with the fabrication process of the project and for developing and conceptualizing the idea for the experimental test set-up apparatus. He cut the notches on the CLT cutoffs because it was too dangerous for me to handle. He also helped me drill the screws and apply the adhesive to the specimens. I really appreciate all the knowledge you shared and help you gave in the Wood Shop. I wouldn't have been able to accomplish my project without you.

I would also like to acknowledge and thank Dr. Peterman for encouraging me to do research and for introducing me to Dr. Clouston and for agreeing to be the co-chair for this project.

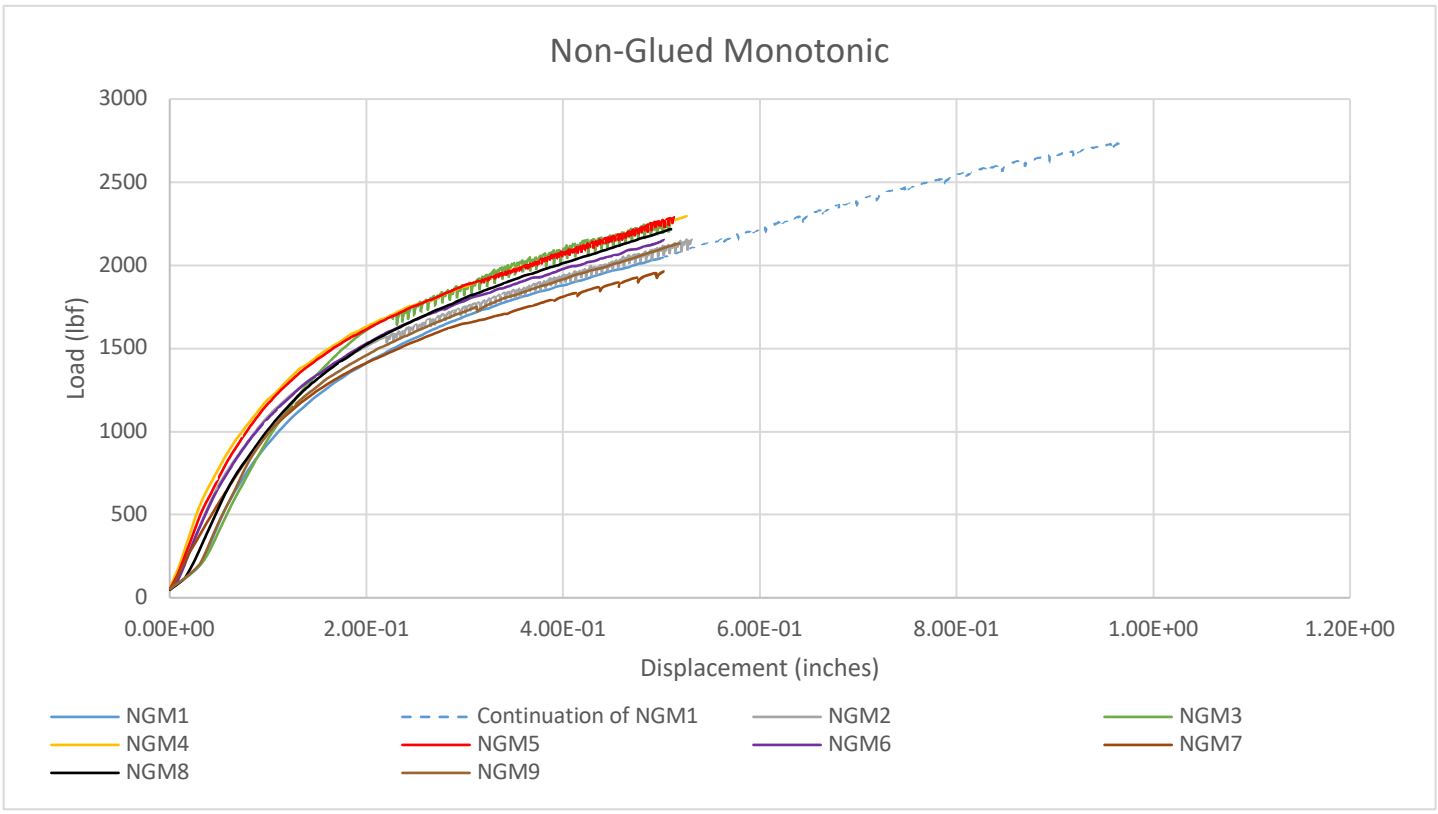
APPENDICES

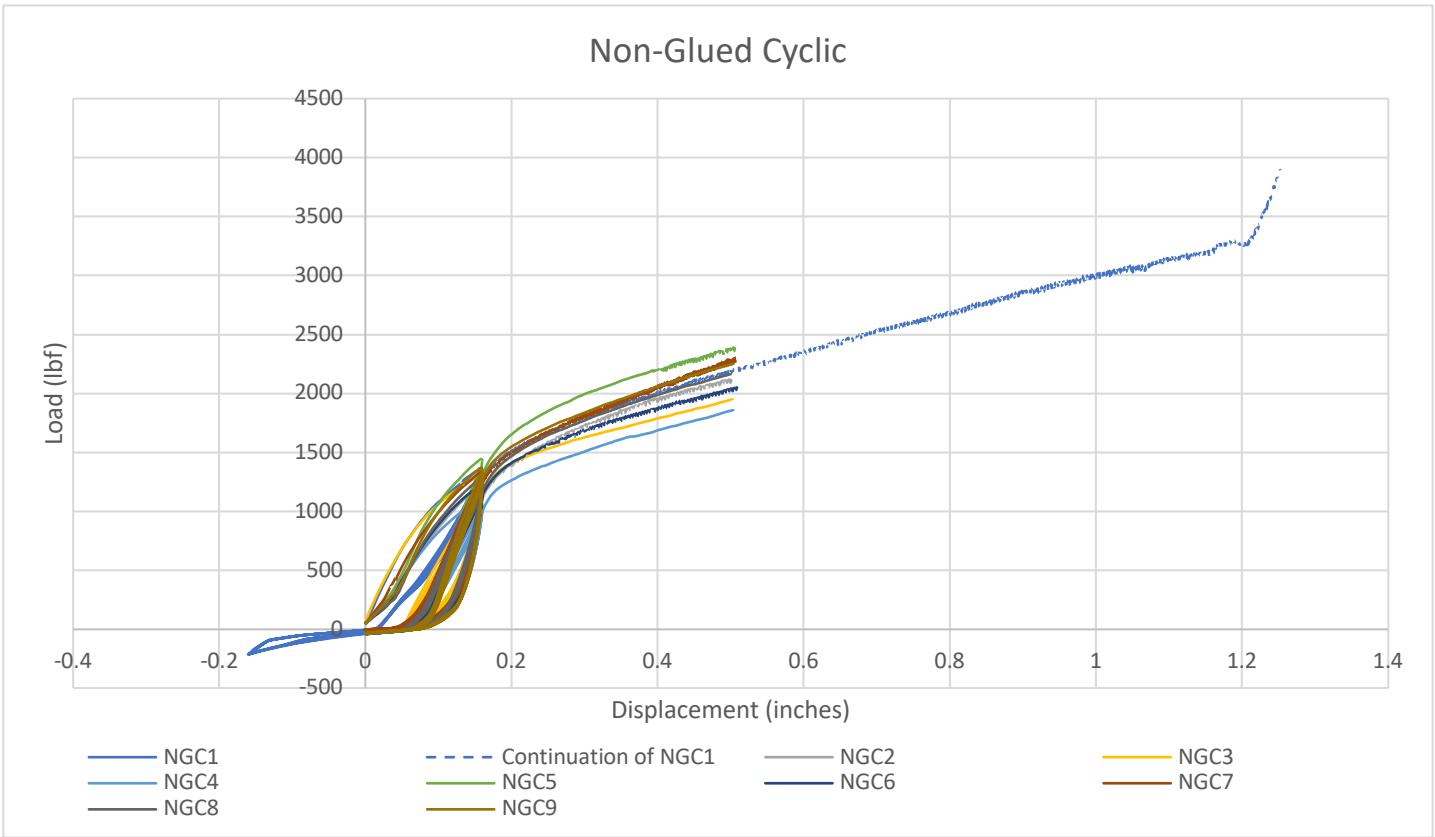
APPENDIX A: MATERIALS LIST

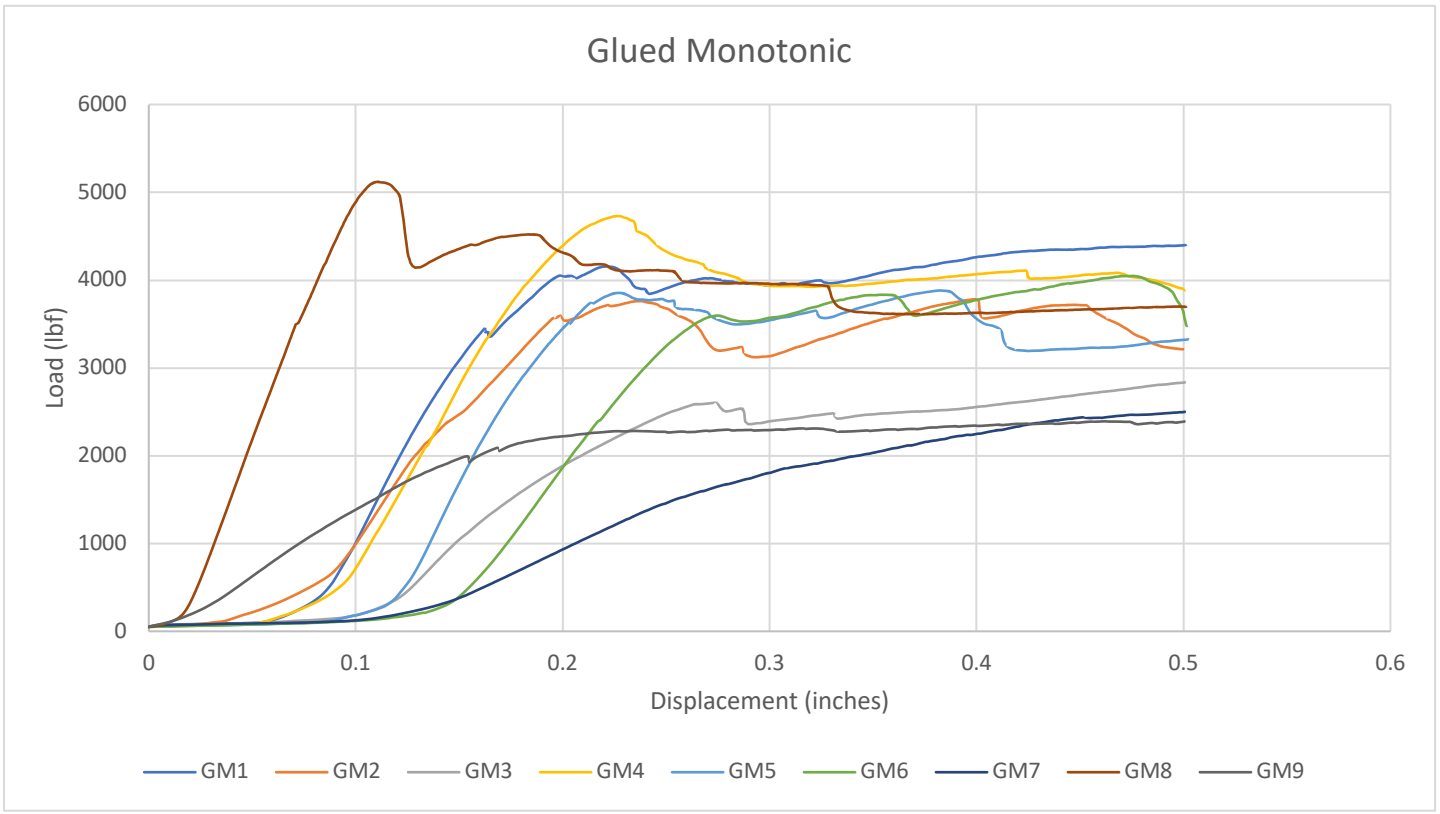
Below is a more detailed list of tools and materials used in this project:

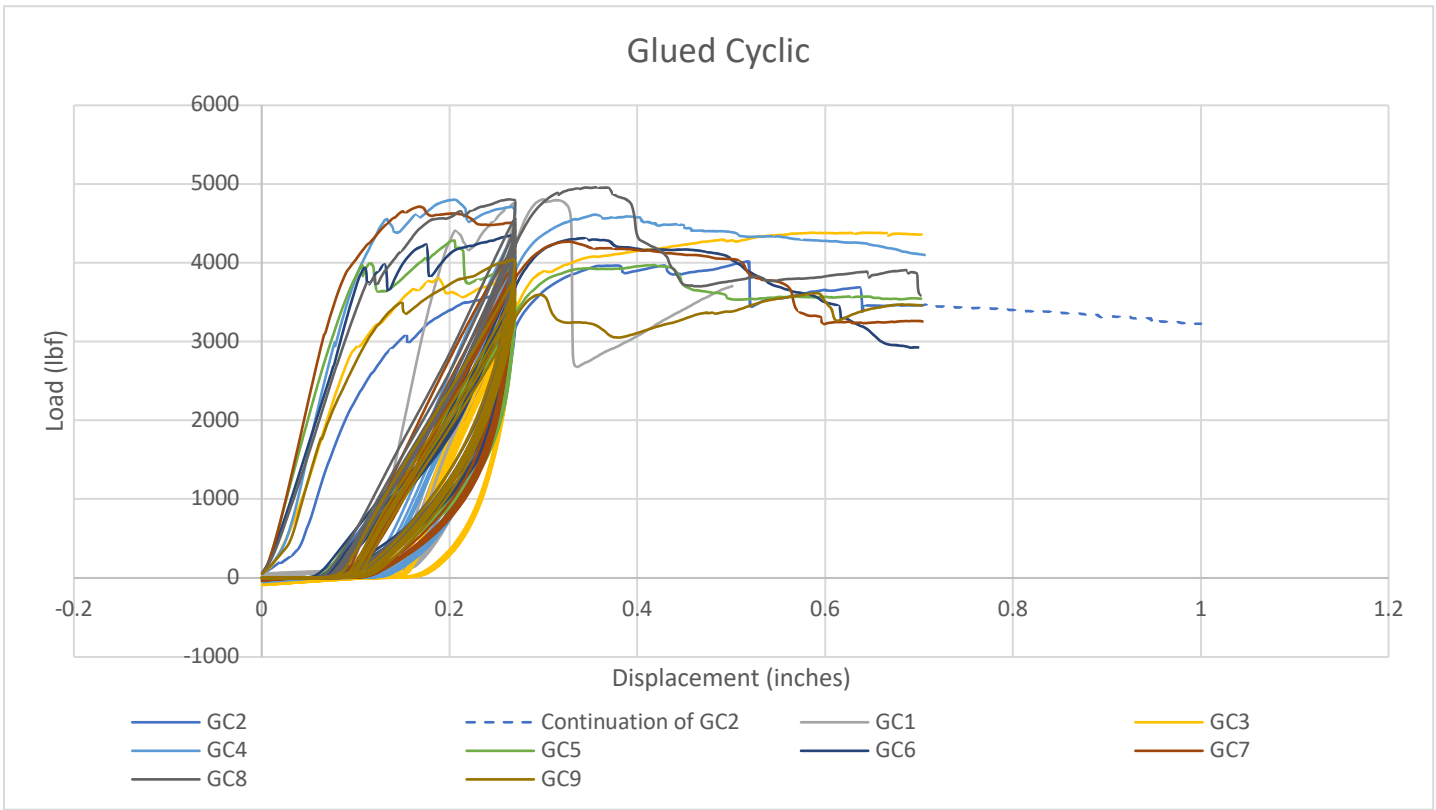
- Eastern Hemlock Cross Laminated Timber (Used in previous research)
- ¾ in. x 4 ft. x 8 ft. PureBond Birch Plywood
- #8 x 2-1/2 in. Philips Bugle-Head Sharp Point Polymer Coated Exterior Screws
- Loctite PL Premium 10 fl. oz. Polyurethane Construction Adhesive
- Chop Saw
- Band Saw
- Table Saw
- Cordless Impact Driver
- Chisel
- Clamps
- Rubber hammer
- Awl
- Square
- Tape measure
- ¾ in. x 19 in. x 2 in. laminated veneer lumber panels
- 3/8 in. – 24 Thread, 3/8 in. long Button Head Hex Drive Screws
- Flat Plate
- Angled plates
- Washers
- ¾ in. Welded Nut
- 18-8 Stainless Steel, M16 x 2 mm Thread Fully Threaded T- Slot Nuts
- M16 x 2 mm Thread Size, 200 mm Long, Grade B7 Medium Strength Steel Threaded Rod
- Class 8, M16 x 2 mm Thread Steel Hex Nuts
- Class 8, M16 x 2 mm Thread Steel Coupling Nuts
- MTS Testing Machine
- T-slot Table

APPENDIX B: GRAPHICAL SUMMARIES FOR EACH TREATMENT






Glued Monotonic
Load (lbf)
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
Displacement (inches)
GM1
GM2
GM3
GM4
GM5
GM6
GM7
GM8
GM9


Glued Cyclic
Load (lbf)
6000
5000
4000
3000
2000
1000
0
-1000
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
Displacement (inches)
GC2
Continuation of GC2
GC1
GC3
GC4
GC5
GC6
GC7
GC8
GC9