Cross laminated timber shear wall connections for seismic applications

by

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# Abstract

This report gives a state-of-the-art summary of current cross-laminated timber (CLT) shear wall systems and connections for seismic applications. CLT panels are gaining popularity as a building material because of their biaxial strength and light weight. CLT panels can be used in building construction not only as floors, but also as shear walls. However, the behavior of CLT shear wall systems under seismic load has yet to be defined. CLT panels are nearly rigid under in-plane loading. While this can be beneficial, structural system qualities that are valuable in seismic loading such as ductility and energy dissipation are difficult to achieve by the panels themselves. Therefore, for the lateral force resisting system to perform as needed, ductility and energy dissipation must come from the connection systems. There is a distinction between a connection and a connection system. The performance of CLT shear walls depends on the behavior of many different connections. CLT shear walls can be categorized into conventional shear walls, and rocking walls. Conventional shear walls follow many of the practices established in light-frame wood shear walls with the use of hold-downs and brackets. Conventional shear walls typically have a base connection with (multi-panel walls) or without (single-panel walls) vertical joint(s). Selection of these two connections can have a noticeable effect on the shear wall behavior. Rocking shear walls allow panel rotation in order to redirect forces into structural fuses in the connection system. The structural fuses vary on the type of rocking wall. These include U-shaped flexural plates (UFPs), energy dissipators, slip-friction connections, and interpanel shear connections. Most of the systems covered in this report displayed favorable seismic performance. Case studies of full-scale buildings that were tested under seismic ground motions are presented. Studies indicated that CLT connections and shear walls have the capability to perform well under seismic loading.

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# Chapter 1 - Introduction

## Basics of CLT

Cross Laminated Timber (CLT) is an engineered wood product in panel form that can be used as both lateral and gravity structural components of a building. Cross lamination is a process of orthogonally layering sawn lumber and therefore creating a structural panel. The benefit of orthogonal layers of wood derives from the nature of wood as a material. Wood is classified as an orthogonal material with varying structural capacity in different axes. In its primary axis (parallel to wood grain), wood is very strong and exhibits a high strength-to-weight ratio. However, perpendicular to its grain, wood is significantly weaker. The varying properties of wood dissuade its use in conditions where load can be experienced in multiple axes. The innovation of CLT panels create a product that is strong in two axes because the different layers have grain running in two directions.

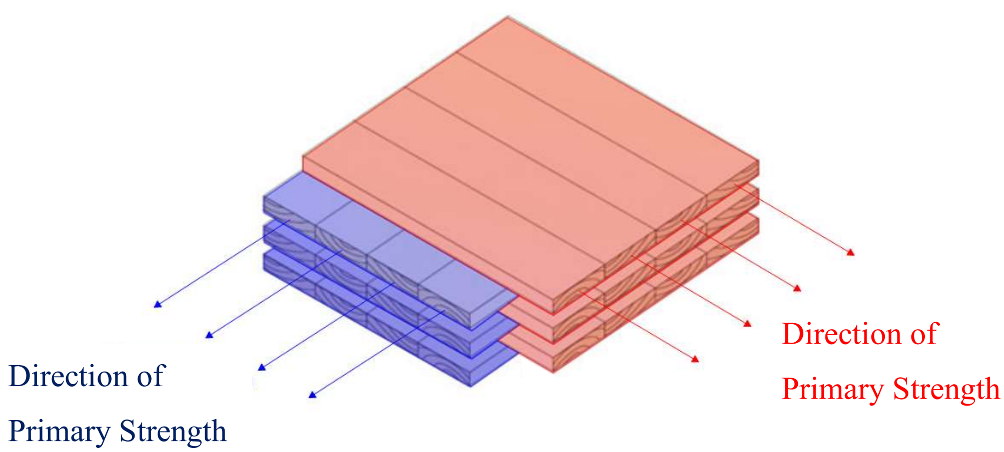



**Figure 1.1 CLT diagram**
**Source: (After Gagnon et al., 2013)**

Several different applications have been established for these panels including floor systems, bearing systems, and shear systems. Floor systems are essentially large horizontal CLT panels that span from other gravity components such as beams or walls. Bearing systems involve vertical CLT panels that transfer gravity loads to foundation elements. Shear systems involve CLT panels transferring lateral building loads to foundations. Shear walls are typically detailed bearing walls. In each of the systems above, strength in two axes is utilized.

CLT is part of mass timber construction. Although possible, the main implementation of CLT construction is not to replace traditional wood construction in the residential or low-rise construction market. Rather, the increased strength of CLT panels compared to typical wood construction allows the pre-engineered wood product to compete with steel and concrete construction in mid-rise and high-rise construction. The high strength-to-weight ratio of CLT panels allows for lighter buildings. Lighter buildings directly correlate to less seismic force and smaller foundations.

## History of CLT

CLT panels have become one of the fastest growing building materials in the building construction industry. Its origins derive from an industrial and academic collaboration in Austria to research and develop a new engineered wood material for mass timber construction (Gagnon et al., 2013). After its lab creation in the 1990s, the product slowly began to gain popularity through the early 2000s. This was primarily in Austria and Germany, but began to spread to the United Kingdom and Scandinavian countries by the end of the 2000s. Canada is another region that has also encouraged the use of mass timber in recent years. The Canadian company FPInnovations, in an effort increase the adoption of CLT, published the CLT handbook in Canada in 2011, and later published a U.S. Edition in 2013 (Gagnon et al., 2013).

Although use of CLT in the United States has been limited, several milestones have developed in the past few years. In the 2015 edition of the International Building Code, a chapter was revised to allow CLT and other mass timber construction to be used (*2015 IBC*, 2015). Additionally, the 2018 edition of the National Design Specification (NDS) for Wood Construction has included a chapter outlining provisions for use of CLT (*NDS*, 2018). Acceptance of CLT in the United States is heavily dependent upon adoption into the code. These code adoptions allow for easier justification of CLT design and construction in the future. Although the number of CLT projects has been limited, growth within the U.S. can be seen through manufacturing. CLT companies in the U.S. such as SmartLam, DR Johnson, Katerra, and Texas CLT LLC have seen a strong growth in the industry. Several of these companies, have or are planning on opening more CLT production facilities across the United States in order to shorten the distance from prefabrication to the jobsite (Franklin, 2019). CLT has grown a significant amount in the past decade.

Several benefits of the material have made it attractive to the building design industry. Wood is significantly healthier for the environment than other building materials such as steel and concrete. The environmental friendliness relies on its renewability and embodied carbon (*100 projects UK CLT*, 2018). Additionally, architects have moved towards wood finishes within buildings for their comfort and aesthetic appeal. Wood structures allow for easier display of wood surfaces in the occupied space. CLT panels have been praised for their acoustic and thermal performance (*100 projects UK CLT*, 2018). Finally, CLT construction is a prefabricated method of construction. As seen in the pre-cast concrete industry, prefabrication of materials leads to safer and more efficient construction, quicker erection of buildings and less time for a project overall. The history of the product shows that its benefits will continue to support its growth in modern construction.

## Importance of Connections

The orthogonal layering of wood in its strong axis creates a remarkably strong panel. Because of the panel's stiffness, the panel demonstrates rigid behavior in experiment and design. This of course does not mean that the panel is indestructible. When failure of the panel is reached, it exhibits little ductility. Ductility is a measure of a material's deformation capability in the inelastic range prior to failure. When designing structures, ductility is important in several areas. A ductile failure behavior is consistent and gives ample warning of the impending failure. A more ductile system allows the engineer to design the structure to move further into the inelastic range of the system and thus using the structure more efficiently to resist design loads. Ductility is important at the connection level as well as the system level. The challenge for CLT structures is that CLT panels offer minimal ductility on their own, favorable structure behavior must come from the connections (Pei et al., 2016).

As will be discussed in this report, one of the biggest challenges for CLT structures is the behavior of its connections. Much of the same information on connector strength used in light-frame wood construction has enabled easy transition to CLT. However, more critical connections such as that of the seismic shear wall need more investigation on the connection systems behavior. Building Lateral Force Resisting Systems (LFRS) include systems which are intended to transfer lateral loads acting on a building to the foundations. The main components of LFRS that CLT panels play an important role include diaphragms and shear walls. Behavior of these systems in terms of ductility, stiffness, energy dissipation is critical to designing them.

As will be seen, the seismic behavior of CLT LFRS is critical to the future of CLT implementation.

In this report, a distinction will be made between connectors, connections, and connection systems. Connectors are established as the individual elements used in a panel system such as nails or screws. Connections are established as the joining of two CLT panels such as a panel-to-diaphragm connection using screws and brackets. Connection systems are established as the collection of different connections that make the panel and its connections behave as a system. Different types of panel connections can be seen in Figure 1.2. For example, a multi-panel CLT shear wall is made of panel-to-panel connections and panel-to-diaphragm connections that account for different forces of the shear wall. The collection of these connections creates a shear wall connection system.

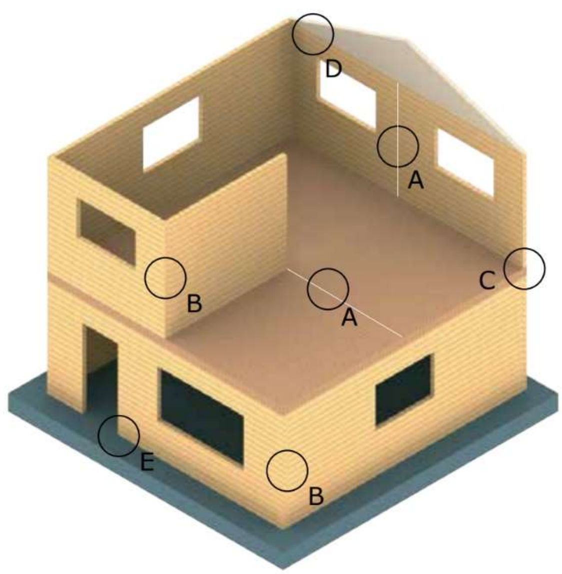



**Figure 1.2 CLT Connection Types**

**A) Parallel panel-to-panel, B) Perpendicular panel-to-panel, C) Panel-to-diaphragm, D) Panel-to-roof, E) Panel-to-foundation**

**Source: (Mohammad et al., 2013)**

In this report, a state-of-the-art summary on CLT shear wall connection systems to resist seismic load will be attempted. Because the dynamic behavior of CLT shear walls is critical, the connections of this system are crucial to the continued growth of CLT buildings in the United States. This report introduces the types of connectors used with CLT panels, general CLT panel connections, and investigates shear wall connection systems. The shear wall connection systems have been segmented into two groups: a conventional system and a rocking system. Conventional shear walls counter the movement of a panel using hold-downs and brackets. Rocking shear walls allow movement of the panel in a rocking motion in order to redirect forces to fuses in the connection system. By exploring the current research and progress of these systems, this report hopes to prove itself as a valuable resource of information on these systems.

# Chapter 2 - CLT Connections

## Introduction

The connection of panels in a CLT structure is vital. This chapter provides basic information about current common CLT connections. Understanding the basics of CLT connections is the prerequisite for discussion of CLT shear wall connections. This chapter introduces industry-standard connections used in different CLT building methods. Most of the information in this chapter is based on the description of CLT connections in 2013 CLT Handbook (Mohammad et al., 2013). Additionally, some connections that were investigated in research are also included.

## Types of Connectors

Connectors in this report are referring to the single element used for connection. Most of the connectors for CLT have been historically used in other types of wood construction. These include self-tapping wood screws (STS), nails, bolts, dowels, and proprietary fasteners made for CLT panels specifically.

**Figure 2.1 Self-Tapping Wood Screw**
**Source: (*GRK fasteners R4 multi-purpose screw*, 2020)**

Wood screws and self-tapping screws are a common connection used with CLT. These connectors are valued for their ease of installation. Self-tapping screws are capable of being installed without pre-drilling holes. Sizes for screws are up to 0.55 inches in diameter and 59 inches in length (Mohammad et al., 2013). As mentioned in the CLT Handbook, STS are "extensively used in Europe for assembly of CLT panels". Design of screws in CLT panels is different from sawn lumber construction because of the laminations. Design capacity of screws must account for gaps in laminations which reduce the capacity of the wood. Depending on the amount of threading, there are partially threaded and fully threaded. Further discussion will be made later as to the effect of these two types in a CLT shear wall connection system.

Nails are another common connector for wood construction. One of the limitations of using nails with CLT relates to nail's ineffective behavior in end-grain of wood. As stated in the 2018 NDS Section 12.2.3.3, "nails shall not be loaded in withdrawal from end grain of wood". On a CLT panel edge there are layers with end grain and layers perpendicular to grain. Theoretically, installers could avoid end-grain nailing, but it's an inefficient process. Therefore, nailing with CLT panels is typically used with metal brackets or other fasteners that allow for perpendicular installation of nails. Nails can also be toe-nailed so that they installed at an angle and eliminating the end-grain condition. There are different types of nails, including common box nails, spiral, and annular shank nails.

Bolts and dowels are among the most common connectors in mass timber construction. With thick panels, bolted connections are easy to inspect. Bolted connections are typically more difficult to conceal. However, their appearance is considered more desirable than other connection types. Bolted connections require pre-drilling of bolt holes which can add more time and labor to installation and coordination. Most of the current research of CLT shear wall connection systems is not focused on bolted connections.

## Platform vs Balloon Construction

Another factor that contributes to the connection style in a CLT project is the type of panel layout. There are two systems of connection in a building with CLT floors and walls, platform and balloon construction.

Platform construction is the process of interrupting walls by floors. The bearing walls are cut at each story level and connected to floor diaphragm at the top and bottom of the panel. This is a commonly used CLT building procedure, especially for multistory projects (Mohammad et al., 2013). The platform method has been the preferred method in both Europe and North American construction because it allows for easier erection of upper stories and simpler connections. Balloon construction on the other hand utilizes continuous walls spanning multiple stories and floor panels are attached to the side of the wall panels (Mohammad et al., 2013). This type of construction is useful for mezzanine levels and some low-rise projects. Difficulties in balloon construction develop with load path due to eccentricity of connections and limitations on panel height. Another form of balloon construction involves LFRS shear walls that do not serve as gravity systems. In this orientation, CLT shear wall panels only accept lateral load and can span multiple stories.

## CLT Connections

The CLT Handbook (Mohammad et al., 2013) has outlined several general connection types for various scenarios on a CLT project. These include provisions for both platform and balloon construction. The follow connections from the CLT Handbook are considered common practice in CLT construction.

### Parallel Panel-to-Panel Connections

The parallel panel-to-panel connection serves several purposes. CLT panel sizes are limited to shipping requirement. Therefore, a CLT wall or floor must be panelized and connected during construction to create large surfaces. Parallel panel-to-panel connections must be rated to transfer both in-plane and out-of-plane load that the panel experiences. In-plane forces are more critical in shear walls, while out-of-plane loading is more critical in floors. Various parallel panel-to-panel connections can be seen in Figure 2.2.

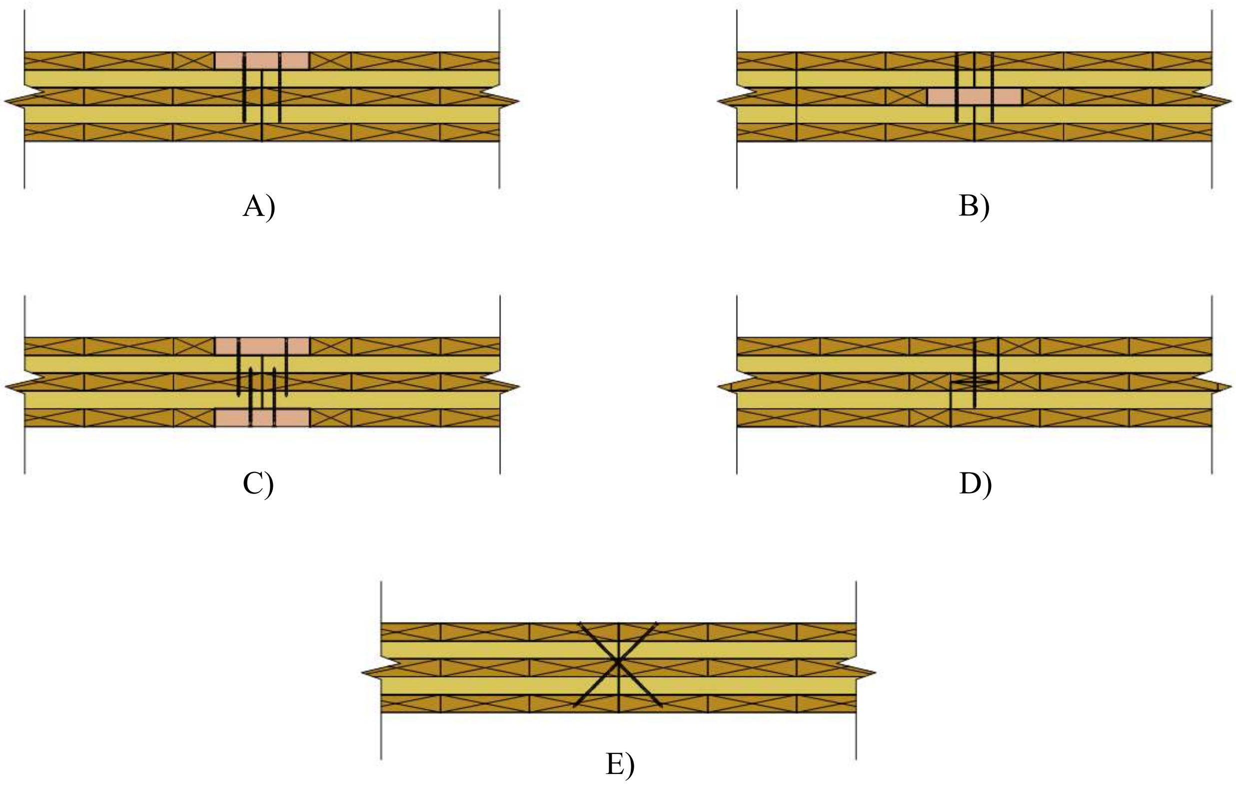



**Figure 2.2 Panel-to-Panel Connections.**

**A) Surface Spline, B) Internal Spline, C) Double Surface Spline, D) Half-Lap Joint, E) Butt Joint**

**Source: (after Mohammad et al., 2013)**

*Spline Joint Connection*

A spline is a classification of connection that uses additional strips of lumber to connect the panels together. This material can be made up of sawn lumber, laminated veneer lumber, a plywood, or even thin versions of CLT. The connection is detailed specifically to allow for a flush transition between panels. Consequently, space for the spline must be profiled in the prefabrication process. Some research has shown that plywood is an ideal material to use for the spline. Because plywood has wood grain oriented in orthogonal directions, connection through the plywood is better suited for the in- and out-of-plane loading that the spline will encounter and reduce the chances of splitting. The connectors for splines are usually self-tapping screws (STS), wood screws, or nails. They are common for different configurations of splines.

There are several configurations for splines. Internal, surface, and double spline are three configurations that are shown in Fig. 2.2A, Fig. 2.2B, and Fig. 2.2C. The internal spline shows the spline in the middle of the panel thickness at the edges of both panels. The internal spline allows for double shear across the connectors. More precise profiling and installation must be considered for this connection type because parts must fit together with one another. Because most of the connection is concealed, the connection has a better visual appeal. The symmetry of connection also helps with out-of-plane loading considerations. European CLT practices have widely adopted double internal splines where two internal splines are used instead of one.

Surface splines are the process of profiling the corners of adjoining panels to allow for the spline material to connect the surface of the panel (Fig. 2.2). There are two forms of surface splines, a single surface spline, and a double surface spline. The double surface spline simply places the surface spline on both sides of the panel. This implies that the single surface spline is weaker than the internal spline because the connectors are in single shear instead of double shear.

A double surface spline requires two splines to be installed therefore matches the strength an internal spline. The double surface spline also requires more labor to install. Surface splines are at a disadvantage for one of the most prized features of CLT, aesthetics. Because CLT is a material that architects like to expose in a building, this puts extra consideration into the connection design. Internal connections offer the visual appeal of a “clean” connection, and are often preferred by architects.

*Half-lap Joint Connection*

One of the other most common form of parallel panel-to-panel connections is the half-lap joint (Fig. 2.2D). In a half-lap joint, adjoining panel edges are notched to allow for an overlap between panels. Long STS are driven through both panels to secure the connection. This type of joint is known for its fast installation because of its simplicity. The connection effectively transfers in-plane shear, but out-of-plane bending can cause a tension stress concentration near the notched area of the joint and split the wood. Out-of-plane forces are more common in floor applications than in wall applications. It is much less likely for wood splitting to develop in a vertical wall.

*Butt Joint Connection*

The butt joint is not specifically mentioned in the CLT Handbook. In this joint, no profiling of panel edges is required because panel ends are connected via diagonal STS (Fig. 2.2E). By inserting diagonally through the panel edges, the screw is developed in both panels. The connection joint will be discussed further for its applications in shear walls.

*Proprietary Connections*

As CLT grows in construction rapidly, alternative forms of connections have been developed. In one case, a proprietary tube connection method is designed for CLT parallel panel-to-panel connections. The system utilizes glued-in or screwed rods that are pre-inserted into the plane of the panel. During field installation, a tube connector is inserted at the rod locations where metal nuts can tighten the metal tube to each panel. As mentioned in the CLT Handbook, this system, "relies principally on the pullout resistance of the screwed or glued-in rods".

## Other Typical Connections of CLT

Other types of connections in a CLT project include perpendicular panel-to-panel connections, panel-to-diaphragm connections, and panel-to-foundation connections as shown in Table 2.1, 2.2, and 2.3 respectively. These connections share similar elements, as described in the tables.

Perpendicular panel-to-panel connections are an important connection for the exterior enclosure of a CLT building. Panel-to-diaphragm connections are a critical component of the lateral force resisting system to transfer lateral load from diaphragm to shear wall. Panel-to-foundation connection has a similar role. It is the final link in the load path for lateral loads of the building. As with any wood construction, special consideration should be given to the moisture exchange between wood and the foundation/ground. As shown in Table 2.3, each foundation connection system has a method of preventing the moisture exchange between these elements. This is achieved through metal plates, other composite materials, or connections that leave gaps at the base of the panel.

### *Direct Self-Tapping Screw Connection*

Because of the ease of installing STS, they are well established in CLT construction. Installation of STS can be made at various angles into CLT panels allowing for more versatility in construction. This allows for sequencing of STS connectors to secure panels to one another as shown in the panel-to-diaphragm connections. Another benefit of the direct STS connection includes the ability to conceal the connection.

*Wooden Profile Connection*

The use of a wooden profile within the wall is very similar to STS connection. However, the wooden profile can add to connection resistance and provide more reinforcement to edges of the panels (Mohammad et al., 2013). Additional wood pieces can also make balloon construction possible as seen in Table 2.2. Wooden profiles can be comprised of various materials including hardwoods, LVL, or plywood. Moisture transfer properties are of high importance for profiles in the panel-to-foundation connections (Mohammad et al., 2013). In some cases, this can be addressed with pressure treated boards or structural composite lumber.

*Metal Bracket & Exposed Metal Plate Connections*

Metal brackets, and in some applications hold-downs, can be used to fasten panels together. Because connectors are entering perpendicular to the panel, the use of nails and screws is permitted. Comparison between these connectors is addressed further in this report. Metal brackets are effective, and easy to install. Some consideration is needed to conceal these connections. Metal brackets and hold-downs are discussed in detail for their application to CLT shear walls. The metal plate connection is a common connection in Europe used to connect the panel to a concrete foundation or podium. The exterior panel surface is flush with the edge of the foundation or podium and a metal plate spans between the two. The plate is commonly connected to the panel with STS and the concrete with lag screws or powder-actuated fasteners.

*Concealed Metal Connection*

Concealed metal plates offer visually appealing and “clean” connections. The T-shaped metal plate is attached on the surface of one wall using screws, then the tab of the metal section fits into the pre-machined slots in the plane of the attaching panel. Dowels or bolts complete the connection by utilizing a double-shear connection between the plate and the panel.

## Summary

Connections of CLT panels have followed similar practice to light-wood construction. A range of connectors such as screws, nails, bolts, and dowels can be used with the material. STS have become a popular connector because of their quick installation and simplicity. Connections in CLT panels depend on the construction method of the building. Platform construction establishes a new platform at each level of the building and serves as the base of walls for the next story. Balloon construction uses continuous walls and as floors connected to the side of walls. A panel-to-panel CLT connection is the joining of two adjacent panels flush to one another. The connection can be made through surface spline, double surface spline, internal spline, half-lap, and butt joints. Perpendicular panel-to-panel, panel-to-diaphragm, and panel-to-foundation connections share similarities in the connection methods. As can be seen in Table 2.1, 2.2, and 2.3, a distinct sequence with each connector can create different types of connections showing the versatility of CLT connections. Most CLT connections are conveniently capable of being transferred from light-frame wood construction. The CLT Handbook shows how these connections are adapted for CLT projects. As the CLT industry grows, many proprietary connections will likely be created that are able to demonstrate their equivalency to the more basic forms of connection.

**Table 2.1 Perpendicular Panel-to-Panel Connections**

**Source: (after Mohammad et al., 2013)**

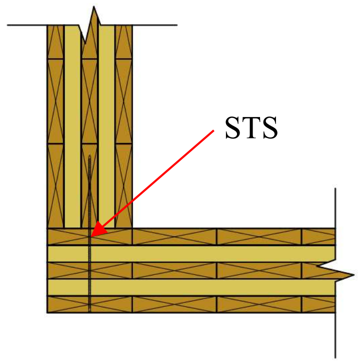
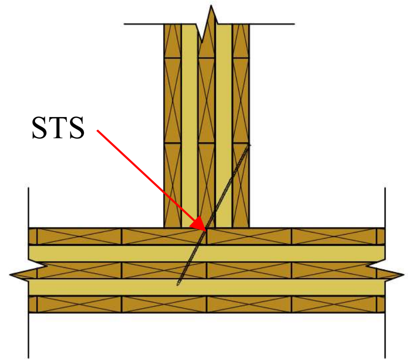
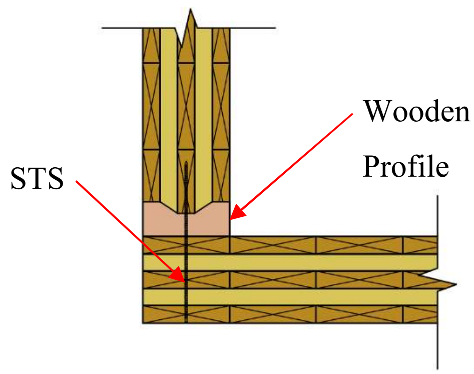
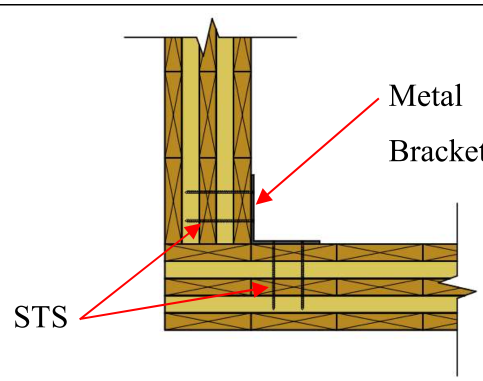
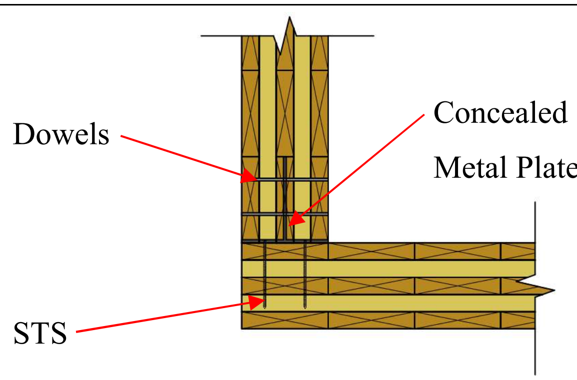
| Connection Type | Diagram |
|---|---|
| Self-Tapping Screws |     |
| Wooden Profile |   |
| Metal Bracket |   |
| Concealed Metal Plate |   |

**Table 2.2 Panel-to-Diaphragm Connections**

**Source: (after Mohammad et al., 2013)**

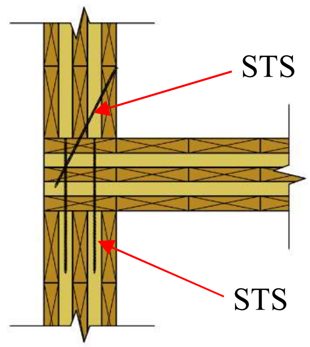
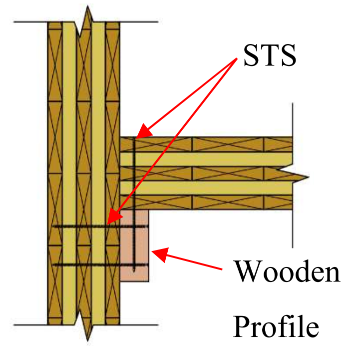
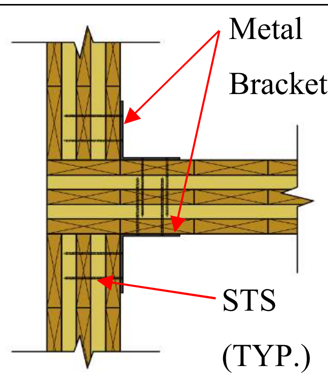
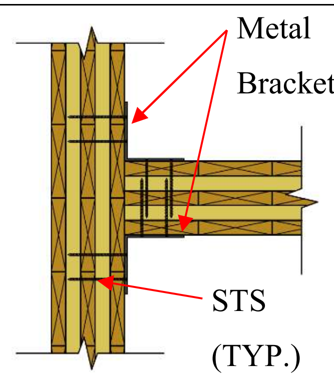
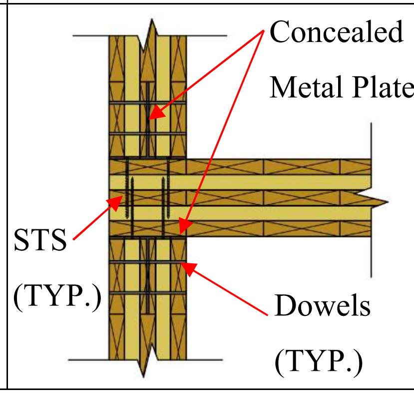
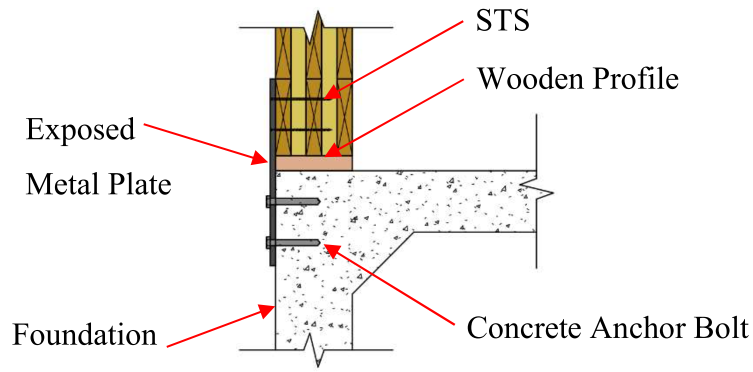
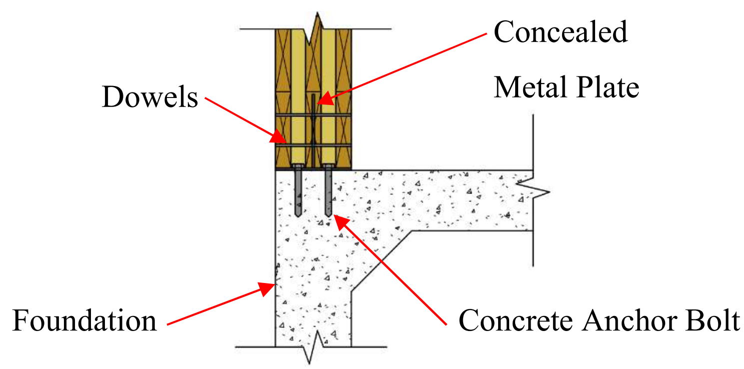
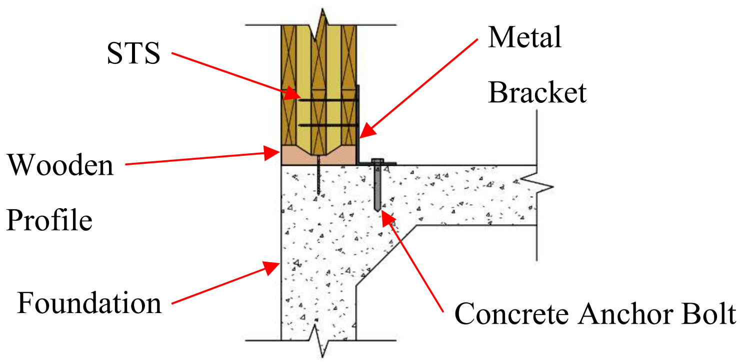
| Connection Type | Platform Construction | Balloon Construction |
|---|---|---|
| Self-Tapping Screws |  |  |
| Metal Bracket |  |  |
| Concealed Metal Plate |  | |

**Table 2.3 Panel-to-Foundation Connections**

**Source: (after Mohammad et al., 2013)**

| Connection Type | Diagram |
|---|---|
| Exposed Metal Plate |   |
| Concealed Metal Plate |   |
| Metal Bracket |   |

# Chapter 3 - CLT Shear Wall Connection Systems

## Introduction

Implementation of CLT within the United States is highly dependent upon the understanding of the system's behavior. Currently in the United States, there is little information within code on the design procedure for CLT buildings. While the gravity load resistance behavior is mostly established, aspects of lateral load resistance are significantly less defined. The regions of the world where CLT construction is growing in popularity tend to be at a lower seismic risk such as the U.K. and Scandinavian countries. Because these regions mostly face wind force governed lateral design, the seismic behavior of the lateral system is less critical. Seismic design presents many obstacles for the undefined systems and limits the use of CLT in LFRS. Energy dissipation and ductility information is needed in design to better understand the behavior of the building. In a CLT building, designing the system without sufficient ductility will lead to high acceleration amplifications and dramatically increase the overturning demands of the structure (Pei et al., 2016). Therefore, through analysis and experiments of the CLT connections systems, better modeling technique and establishing proper seismic design coefficients will facilitate design and implementation of CLT buildings.

Several different CLT shear wall connection systems have been studied for better understanding of their behavior. They include two main categories of conventional CLT shear walls and rocking CLT shear walls. This chapter is a summary of some of these studies. The primary goal of any system is to ensure life safety in the event of a major earthquake or wind event. However, as will be discussed later in this chapter, some systems are capable for designing past the standard of life safety. Therefore, when applicable, the failure mode and repair method of the shear wall connection system are discussed. Because many of the following studies were not conducted in the same test, comparison between systems is difficult. General trends across differing research are presented.

## Conventional CLT Shear Wall Connection Systems

Conventional shear walls are defined in this report as similar to shear walls in light-frame wood construction. The connections directly counter movement of the panel. As seen in light-frame wood construction, brackets and hold-downs are used to restrain the wall panels. Hold-downs are place at the edges of shear walls to handle overturning tension loads. Brackets transfer the shear component of the load acting on the wall. This system serves as the basis of conventional CLT shear walls. The main difference between the two lies in the stiffness of the wall itself. Where light-frame wood shear walls rely on sheathing for shear transfer between diaphragms, CLT panel shear walls use the entire solid section for shear. Because CLT panels are so rigid, in-plane shear deformation is negligible. This shifts seismic demand to the connections.

The following section summarizes the connection methods for conventional CLT shear walls and offers general statements as to improving the ductility of these connection systems. The order of information first covers base connections which involve panel-to-diaphragm and panel-to-foundation connections. Then, the variation of connections will be discussed for the vertical connections, also referred to as panel-to-panel connections. A discussion over single-panel shear walls and multi-panel shear walls is discussed. All the conventional CLT shear wall connection systems found are for platform type construction. Some of the tests involved stacked shear walls, where two stories of shear walls were tested, but in these cases the diaphragm always interrupted the wall at story levels.

## Base Connections

The base connections of a conventional CLT shear wall will either be a panel-to-diaphragm or panel-to-foundation connection. The most common form of this connection is a combination of brackets and hold-downs. Although there are several possibilities for the panel-to-diaphragm and panel-to-foundation connection as described in chapter 2, seismic research has been conducted on bracket and hold-down connections, anchor tie-down systems (ATS), and toe-screwing.

The relationship between hold-downs and brackets has been conventionally described that hold-downs will account for overturning of the structure under lateral force, and brackets resist the shear. It has been studied that in a CLT structure, hold-downs have high amounts of strength and stiffness for tension and significantly weaker in shear. However, brackets have shown favorable behavior in both shear and tension (Gavric et al., 2014). For this reason, Gavric et al., 2014 suggested in their study that correct design of these walls would require assuming brackets can also counter overturning force (Gavric et al., 2014). This information in addition to other experimental studies are critical to characterizing the hold-down bracket system and are useful for model development. In an overview of several different factors, shear walls with hold-downs in combination with brackets improve the seismic performance of the system when compared to shear walls with only brackets (Shahnewaz, 2018; Popovski & Karacabeyli, 2012). The connection of hold-downs and brackets can be concrete anchoring when attaching to the foundation. When connecting these elements to panels, the most common methods include nails and screws. It was found that CLT shear walls display adequate performance when hold-downs and brackets are connected with screws or nails (Popovski & Karacabeyli, 2012). The hold-down and bracket connections continue to be a popular method in the transition to CLT construction.

Another popular method taken from light-frame wood buildings is the use of anchor tie-down systems (ATS). Continuous steel rods run through stacked CLT shear walls and act as overturning resistance. Therefore, the ATS is located at the edges of the shear wall (van de Lindt et al., 2019). In one design, detailing ensured that the rods were used only in tension by allowing the rods to disengage in compression (van de Lindt et al., 2019). Because the ATS replaces hold-downs, shear connectors in the form of brackets are still utilized at the base of panels. Testing of a CLT shear wall with ATS found that it met design objective of life safety and collapse prevention (van de Lindt et al., 2019). Therefore, this is another possible design for the future of conventional CLT shear walls.

Toe-screwing, as mentioned in chapter 2, is the diagonal installation of screws at the edge of a panel into the CLT diaphragm. The use of toe-screwed connection has been debated for its behavior and likelihood to be adopted as a base connection for a shear wall. A study conducted by Popovski & Karacabeyli (2012) stated that the use of toe-screwing at 45 degrees created a connection with little energy dissipation and resistance and is therefore not recommended for seismic regions (Popovski & Karacabeyli, 2012). Additionally, once the connection has been deformed, the damage created is rarely reparable.

However, more recent studies have showed promise for the toe-screwed connection. Tests involving STS with washer heads displayed a different failure mode due to the larger area of the head and hence much better seismic performance (Fitzgerald, 2019). Fully threaded (FT) screws without a washer head, and partially threaded (PT) screws with a washer head were both tested. The PT screws with washer head displayed better cyclic performance with gradual plastic wood failure while FT consistently fractured in failure. When evaluating the shear wall with toe-screwed base connections with the panel, the author concluded that headed PT STS is a viable option for seismic LFRS.

## Vertical Connections

Another component of conventional CLT shear walls is the vertical, or panel-to-panel joint. Vertical joints are not required to create a shear wall. As will be discussed further, there are advantages to using multi-panel shear walls as opposed to single-panel shear walls. The addition of this joint allows for better ductility and greater energy dissipation. In order to design for seismic actions, buildings provide ductility and energy dissipation through walls (Loss et al., 2018). Developing the joint for preferred seismic response varies upon the connection type and connections, as well as the orientation of the connectors. The following section will discuss nail and screw connectors in differing types of panel-to-panel connections including spline, half-lap, and butt joint.

The orientation of STS can have drastic effects on the behavior of the system. The two forces that STS are typically associated with are shear and withdrawal. Withdrawal force acts parallel to the direction of the screw and acts to "pull out" the STS. Shear acts perpendicular to the direction of the screw. Experiments have shown that STS acting in shear displayed moderate ductility and large displacements compared to STS acting in withdrawal which constituted stiffer and stronger connections (Hossain et al., 2015). The movement between adjacent panels induces force to the vertical joint connection which is responsible for restraining the sliding. Therefore, STS angle of installation will change the primary force between withdrawal and shear. When screws are installed on the horizontal plane, the STS will act in shear. When STS installation is tilted from the horizontal plane, the sliding motion between panels pull on the STS, making them act in withdrawal. STS in panel-to-panel connections such as butt joints may be installed at two different angles. One angle to make the connection of the panels, and another to establish shear or withdrawal behavior.

Panel-to-panel connection types seen in tests include the surface spline, half-lap and butt joint. STS's in spline joints are installed perpendicular to the connection and therefore achieved ductility and deformation capacity, despite cracking in the spline was observed in some tests (Hossain et al., 2015). Spline joints have also been tested to compare STS and nail connectors. Taylor (2019) concluded that nails are more ductile than STS but were weaker. However, the nails perform better for cost when compared to STS. Parametric testing showed that half-lap joints performed better than spline joints under seismic loading (Shahnewaz, 2018). Half-lap and butt joints have shown to be stiff connections when STS are acting in withdrawal (Hossain et al., 2015). It was also shown that when half-lap and butt joints have STS that act in shear, they are more ductile (Hossain et. al., 2015; Loss et al., 2018). It is recommended that STS in shear be used to create ductile walls in seismic loads as opposed to withdrawal (Loss et al., 2018). Finally, an alternative configuration for half-lap STS has been explored. Because stiffness and strength can also be favorable traits in design, installing STS in a combination of shear and withdrawal can lead to increased ductility and strength for a system (Hossain et al., 2018). This combination is achieved by installing some screws perpendicular, and some at an angle into the half-lap joint. It was found that the combination produced nearly equivalent stiffness when compared to a withdrawal only layout, and nearly equivalent ductility when compared to a shear only layout (Hossain et al., 2018). In conclusion, the orientation of connectors and connection type will determine the seismic behavior of the vertical joint.

## Single-Panel Shear Wall vs. Multi-Panel Shear Walls

A single-panel shear wall is a single CLT panel acting as a shear wall. Thus, there is no vertical joint between panels in this system. The behavior of single shear walls relies almost entirely on the panel-to-diaphragm/foundation connections. Also, width of single-panel shear walls is limited to panel width. Multi-panel shear walls have one or more vertical joints. This allows for the aspect ratio of the multi-panel shear wall to be customized. The aspect ratio of CLT shear walls is important in determining the deformation and the resulting forces in the shear wall connection system. CLT shear walls, as mentioned before, are very stiff. The panels experience a combination of sliding and rocking motion. As the aspect ratio, or height-to-width ratio of the panel increases, the motion transforms from sliding dominant, to rocking dominant (Shahnewaz et al., 2019). Rocking dominated motion creates shear wall connection systems that incorporate more deformation capacity (Amini et al., 2018). The increased aspect ratio of panel provides more deformation capacity for the structure. Therefore, multi-panel shear walls allow for more favorable aspect ratios to be selected and therefore increase the deformation capacity of the system.

## Implementation of Conventional CLT Shear Wall

Conventional CLT shear wall connection systems have been the central focus of research on CLT LFRS. Because this system relies on simple connections, it is a method that favors constructability and uses proven connectors through years of construction experience. One of the obstacles for using conventional CLT shear wall connection systems is that the seismic design parameters have not been established in code yet. This presents difficulties for the design and implementation of CLT shear walls. However, a process is in place to define conventional

CLT shear wall systems. Once this process is complete, design and implementation of traditional CLT shear walls within the United States will be much easier.

To use code prescribed procedure for seismic design, performance of the lateral force resisting system shall be known. In particular, the response modification coefficient (R), overstrength factor ($\Omega_0$), and deflection amplification factor ($C_d$) are essential for engineers to use the system in seismic application. Recent studies applied the procedure in the FEMA P-695 in combination with test data to calibrate the seismic design parameters for conventional CLT shear wall systems. Amini et al. (2018) conducted tests on shear wall connection systems involving bracket panel-to-foundation/diaphragm connections and a metal plate panel-to-panel connection, both of which are connected via common nails. Pei et al. (2013) used previous testing data and a performance based design approach to estimate the R-factor for conventional CLT shear walls, and concluded that R = 4.5 for CLT walls. This study also found that the building outperformed the current North American wood-framed building and was able to, "limit structural damage to a minimal level even for maximum credible earthquake (MCE) events near Los Angeles, CA" (Pei et al., 2013). Preliminary evaluation of conventional CLT shear wall system suggest the system can perform well in seismic regions. With seismic design parameters incorporated in the code in the near future, CLT shear walls will be a viable option in seismic applications, especially for CLT buildings.

### Innovative Coupled Shear Wall

Because CLT buildings are new, some researchers have explored new methods to approach CLT shear walls. Pei et al. (2017) have proposed a method to combat overturning in large CLT buildings. Instead of relying on a single CLT shear wall stack to transfer lateral load down to the foundations, this method suggests that the CLT diaphragm used in the building is sufficient to act as a coupling element between neighboring CLT wall stacks. In other forms of wood construction, the diaphragm is simply not stiff/strong enough to act in this manner. CLT floors are much stronger elements and have enough inherent strength to act primarily against building overturning. Therefore, the connection system of this shear wall type relies on shear transfer between CLT shear walls to the diaphragm (sliding action) through brackets. But, instead of designing every shear wall stack for overturning, it accounts for overturning with multiple shear wall stacks. The compression is resisted by the CLT wall, and tension is resisted by anchor tie-down systems (ATS). These connections, in addition to the panel-to-panel connection of the diaphragm, create this innovative coupled shear wall connection system.

The major advantage of this system is in detailing. In a building with isolated shear wall stacks, each stack needs to have tie-down and compression elements on each side of the shear wall. The installation of these tie-down elements can increase cost of the project. However, with a coupling CLT floor, the shear transfer through the flooring allows for ATS installation only near the perimeter of the building where wall stacks transfer the load down to the foundation. The study concluded that the proposed system showed good potential in CLT platform construction.

## Rocking CLT Shear Wall Connection Systems

Rocking shear walls have been defined in this report as shear walls with connections that enable some form of rocking motion of panels, where seismic force can be redirected into "fuses" within the system. Hence, ductility and energy dissipation can be added to the connection system in order to increase the seismic performance of the wall. There are different ways on how the system achieves rocking behavior, but it can be mostly sorted between post-tensioned (PT) and non-post-tensioned (non-PT). Another aspect of these rocking walls is "self-centering" because the panel "rocks" back to its original position. Whereas conventional CLT shear walls are almost entirely platform type construction, some proposed rocking CLT shear walls are for balloon construction. The following section explores the different proposed connection systems for CLT rocking walls.

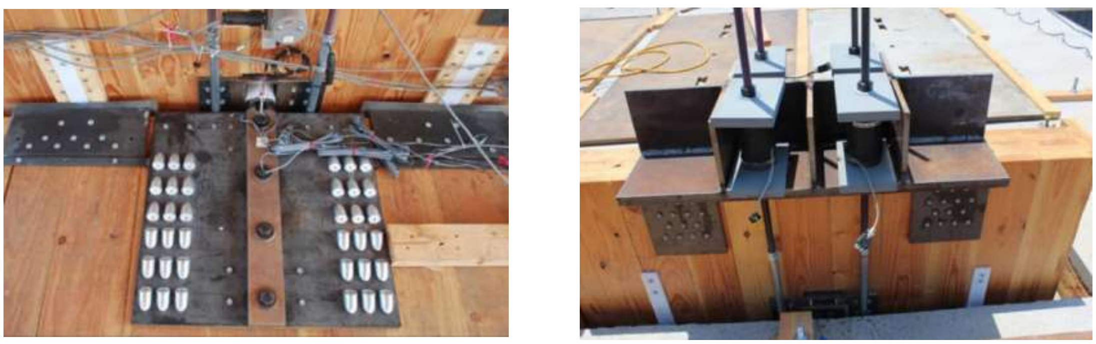
### Post-Tensioned Rocking Wall Connection Systems

Post-tensioning is a practice in construction of inserting steel rods through a structural member and overtightening the rod after installation. The overtightening of the rod can achieve several purposes. According to Ganey et al. (2017), the PT acts first as the method of connecting the shear wall to the diaphragm. When lateral load acts on the wall, the panel itself will counter the load through shear or flexure. Finally, a lateral load is reached that causes the shear wall to tilt. As the tilt of the panel increases, the PT rod running through the panel elongates. There are several limit states for self-centering CLT shear walls. PT yielding is one of the last (highest strength) limit states (Akbas et al., 2017). Before the ultimate limit state is reached, the PT acts elastically to restore the original location of the panel in cyclic loading. Because the post-tensioned rods are elastic, they will not serve to dissipate energy from the system and additional energy dissipation devices are needed (Ganey et al., 2017).

Ways to connect PT in rocking wall systems vary from project to project. The base of the connection can be angles or steel saddles that sits on the foundation element. The saddle/angles sandwich the panel to brace the panel out-of-plane (Pei et al., 2019). The angles are then fastened to the foundation element so that when post-tensioning is applied, the foundation element is engaged with bearing on the panel. In most rocking wall construction, the compression of the CLT panel on the foundation, which being braced out-of-plane, is the only connection mechanism to the foundation (Akbas et al., 2017).

*Balloon Construction*

In balloon construction, PT and CLT rocking walls extend through floor and are continuous for the height of the structure (Pei et al., 2019). See Figure 3.1, the top of the PT connection in balloon construction is similar to its base. A bearing plate on the top of the rocking wall connects the PT and wall together. In order to engage the diaphragm, shear connections are used to transfer lateral load to the rocking wall, but not vertical loads (Pei et al., 2019).



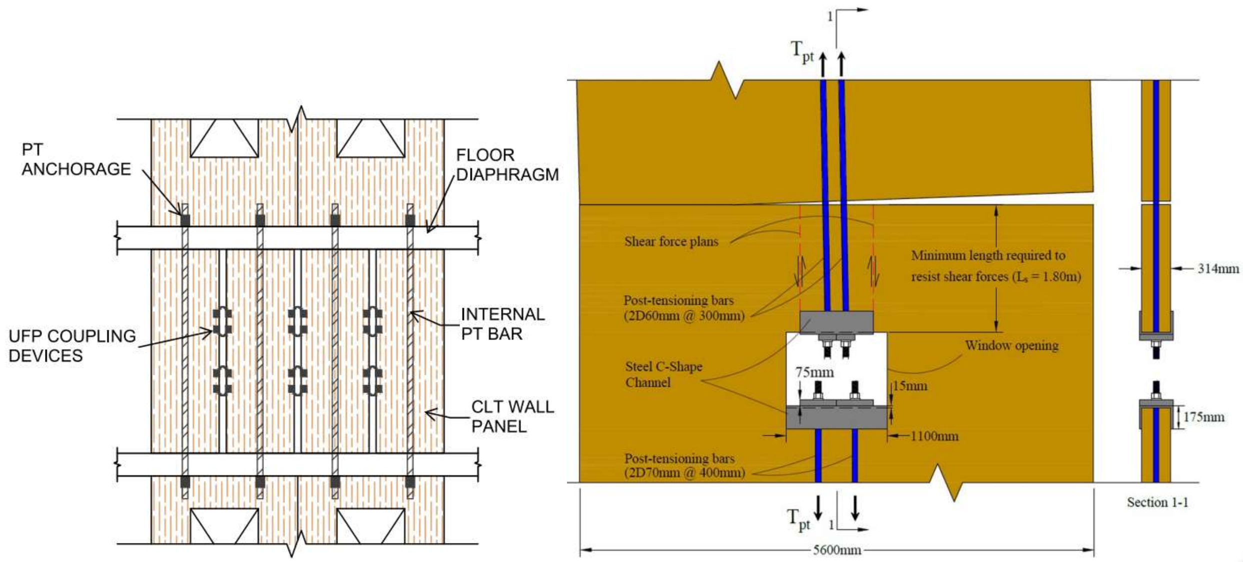
A) Diaphragm to wall panel shear key B) Top of wall PT connection

**Figure 3.1 Balloon Rocking Shear Wall Connections**
**Source: (Pei et al., 2019)**

*Platform Construction*

In platform construction, PT is typically terminated and reapplied for each story level. The base connection of PT to foundation element has the same configuration as balloon construction. One method of creating story-to-story PT connections involves connecting the PT to the diaphragm (Ganey et al., 2017). This connection would likely need steel bearing plates or saddles in order to protect CLT from crushing. Another PT connection method involves running

PT in the center of the panel and connecting the PT in the middle of the panel (Pilon et al., 2019). As shown in Figure 3.2B, the opening in the panel allows for PT to bear on steel channels. The study of the gap opening PT connection method (Pilon et al., 2019) shows that this connection simplifies the design and installation and creates a more economical connection system.




A) Connection at diaphragm level B) Connection in the middle of the panel

**Source: (Ganey et al, 2017)** **Source: (Pilon et al., 2019)**

**Figure 3.2 Connection methods of PT**

Each PT system relies on additional components to generate added ductility and energy dissipation. By incorporating elements designed to yield, the connection system can be pushed into the inelastic region and display ductile behavior under seismic loading. These "fuses" within the connection system can typically be replaced so that structures can be repaired quickly after a major seismic event. The following section shows the variation in PT rocking CLT shear wall connection systems through the varying fuses and connection orientations.

*U-Shaped Flexural Plates*

U-Shaped Flexural Plates (UFPs) serve as a panel-to-panel connection between two adjacent rocking shear walls (Figure 3.3). Therefore, this system can only be used in buildings with side-by-side rocking walls. The rocking motion between the two walls creates stress on the UFP and, at large seismic events, the middle portion of the UFP will eventually be pushed into its inelastic region and more deformation will occur. The connection of UFP can be achieved through a steel saddle or embed plate into the panel, and bolts or weld connecting the UFP to the embed plate. After the seismic event has yielded the UFP, the UFP can be replaced (Ganey et al., 2017).

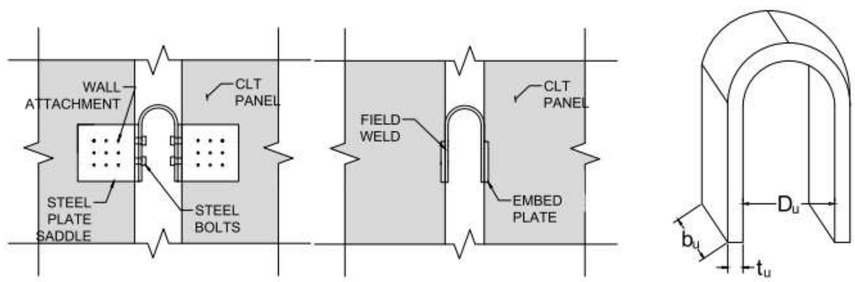
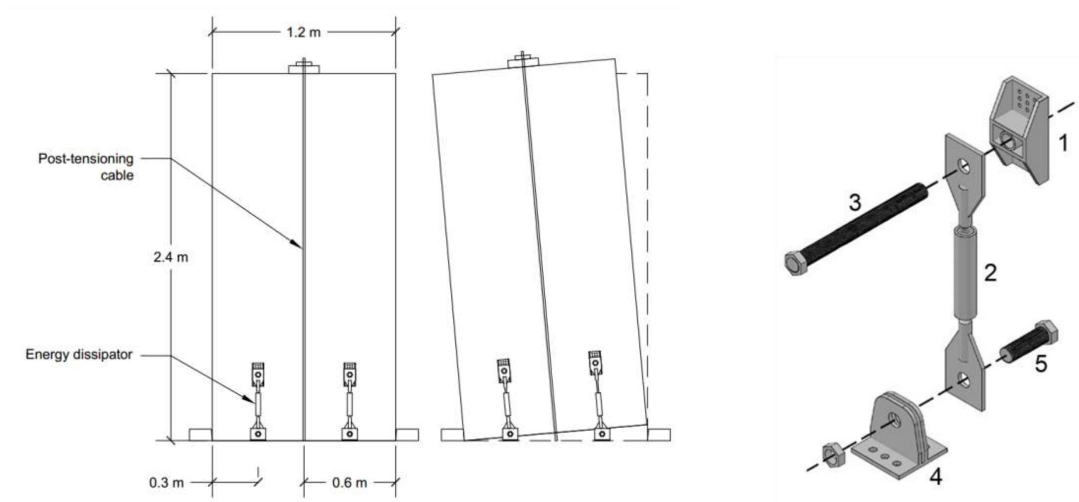



**Figure 3.3 U-Shaped Flexural Plates**
**Source: (Ganey et al., 2017)**

In testing, the connection system with UFPs showed ductile response, good strength and energy dissipation (Ganey et al., 2017). In a separate testing program with balloon framing, the CLT rocking walls displayed resilient performance at maximum considered earthquake levels (Pei et al., 2019). Although specifics of the performance are difficult to compare, a general conclusion is that CLT rocking wall connection systems with U-shaped flexural plates used as energy dissipators are capable of resisting large seismic events.

*Energy Dissipators*

Taken from precast concrete design, externally mounted energy dissipators can be used to bring ductility to the CLT rocking shear wall (Kramer, 2014). These dissipators were mounted at quarter points on the bottom of the panel using connection procedures in the NDS (Figure 3.4A). The steel dissipators are in tension exerted by the rocking panel and will yield under a major seismic event (Figure 3.4B). The dissipators are designed for easy replacement after major events. Buckling needed to be considered in designing the dissipators. The study suggested that the proposed energy dissipator is adequate for potential application to a CLT rocking wall system.

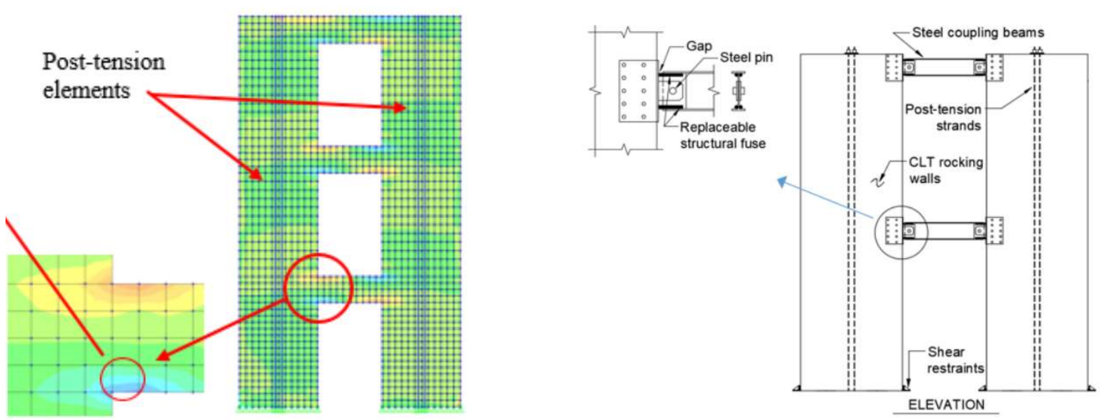



A) PT rocking wall with dissipator diagram B) Isometric of dissipator

**Figure 3.4 PT rocking wall with energy dissipators**
**Source: (Kramer, 2014)**

*Coupling Beams*

Coupling beams are a concept in other seismic systems that may be implemented into CLT rocking shear walls. The use of coupling beams spanning between shear wall stacks as seen in Figure 3.5. The distance between panels can be useful for architectural purposes such as door or window openings (Dowden & Tatar, 2019).  The behavior of coupled beams between CLT rocking walls is similar to the behavior of UFPs described earlier with the intent of energy dissipation for the connection system.  When investigating the use of monolithic or attached CLT panels to act as coupling beams, results show that large concentrations of stress are present at the beam-to-wall connection and would be difficult to repair (Dowden & Tatar, 2019).  The use of CLT as the coupling beam may be too impractical to implement.  However, the use of steel coupling beams is more practical.  As in other designs of coupling beams, pin connections between the beam and the wall can also incorporate steel fuses.  These steel fuses create predictable limit states for the design and are easily replaceable.




A) CLT coupling beam B) Steel coupling beam

**Figure 3.5 Rocking wall with coupling beams**
**Source: (Dowden & Tatar, 2019)**

## Non-Post-Tensioned Rocking Wall Connection Systems

While PT rods serve as a means of restoring the shear wall after loading, rocking CLT shear walls without PT achieve the restoration in different ways.

*Resilient Angled Slip-Friction Joint*

The resilient slip-friction (RSF) connection is comprised two outer plates, and two inner plates (Hashemi et al., 2018). Each plate has angled groves that when assembled, the inner plates are equally matched by the outer plates. As can be seen in Figures 3.6 and 3.7, the plates are connected by four bolts. The bolts are also fitted with Belleville springs which will resist the expansion of the plates. The RSF is located on the lower corners of the rocking panel working as hold-downs. However, these connections will allow for the rocking of the panel by plates sliding past one another. The angled grooves translate sliding movement into expansion of the plates. This expansion is resisted by the Belleville springs that push the plates back together. The connection acts as the self-centering mechanism of the panel.

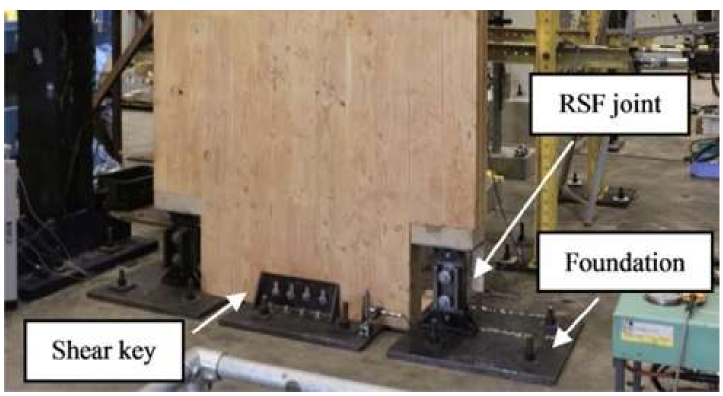
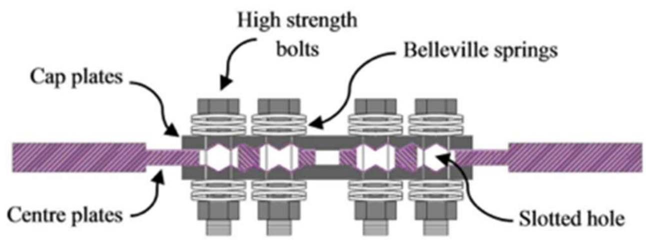



**Figure 3.6 Base of shear wall with resilient slip friction connection**
**Source: (Hashemi et al., 2018)**

Hashemi et al. (2018) tested a CLT shear wall system with the RSF joint. Bottom corners of the CLT panel were removed to create room for the RSF connectors. The RSF is connected to the panel via screws that are installed in the plane of the panel. A shear key connects the center of the panel to the foundation (Figure 3.7). The shear key has slotted holes that allow for uplift and rocking of the panel. Experimental results showed that the RSF was able to dissipate energy at a desirable rate through the friction between the plates. This study concluded that the connection system displayed excellent behavior and has potential for seismic application in CLT rocking shear walls.




A) Cross-section diagram

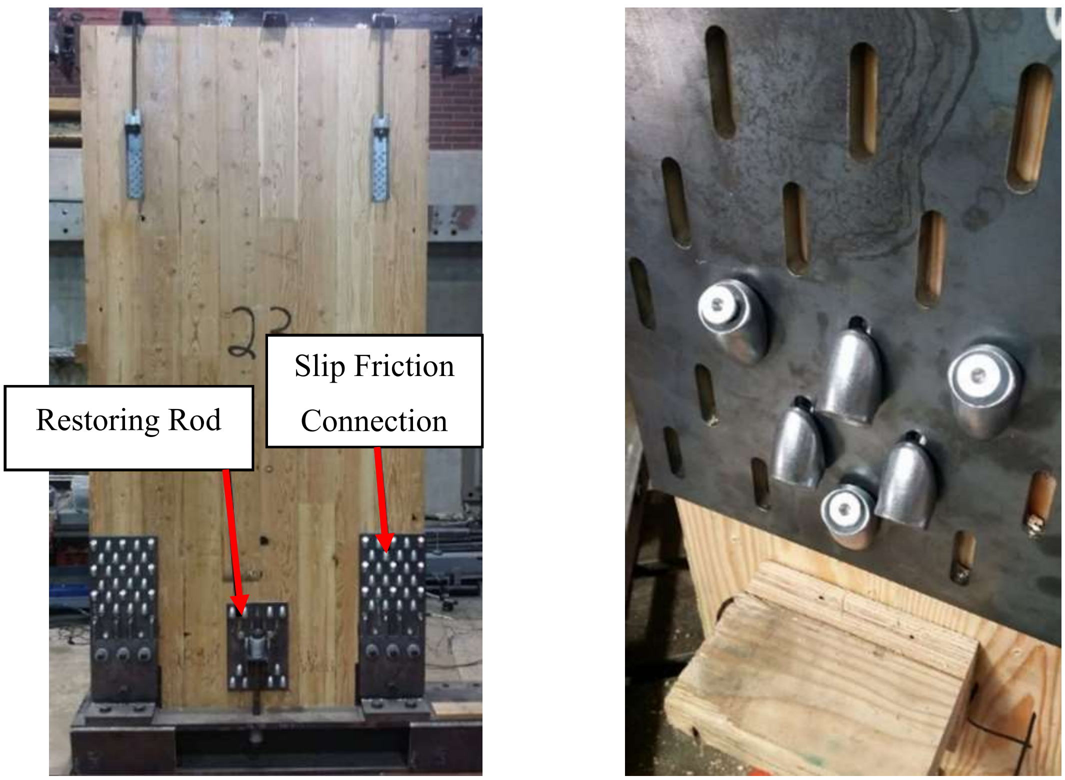
B) Assembled isometric view

**Figure 3.7 Resilient slip friction connection**
**Source: (Hashemi et al., 2018)**

*Slip-Friction Connection*

There is a more common version of slip-friction connection. Fitzgerald (2019) conducted tests on the CLT rocking wall connection system with the slip friction connection (SFC) described below. Similar to the RSF discussed above, the SFC acts as a hold-down and requires the lower corners of the panels to be removed to allow room for the connections. STSs connect the slotted plate through a 45-degree angled washer that conforms to the slot in the plate (Figure 3.8). The interaction between the washer and the plate creates the desired slip-friction. Therefore, the STS connecting the panel need to have a stiff connection with little deformation. The 45-degree screw pattern ensures that slip occurring in the system is between the washers and the metal plate, not the deformation of the STS.

The self-centering abilities of the panel are generated from a restoring rod at the center of the panels base. The restoring rod is very similar to PT, but instead of applying compression to the whole height of the panel, it relies on 45-degree STS to secure the rod connection to the side of the panel (Figure 3.9).  The restoring rod uses Belleville washers to help generate the tension. This self-centering mechanism could be an easier construction method over full-height PT for mid-to-high-rise CLT buildings.  Another test was completed without restoring rods as well.  The gravity loads on the panel with limited rocking deflection were able to re-center the panels upon unloading.  Overall, the system behaved in a predictable manner and modeling of the results should be possible.  Further tests are needed to understand the strength of the restoring rod over time.



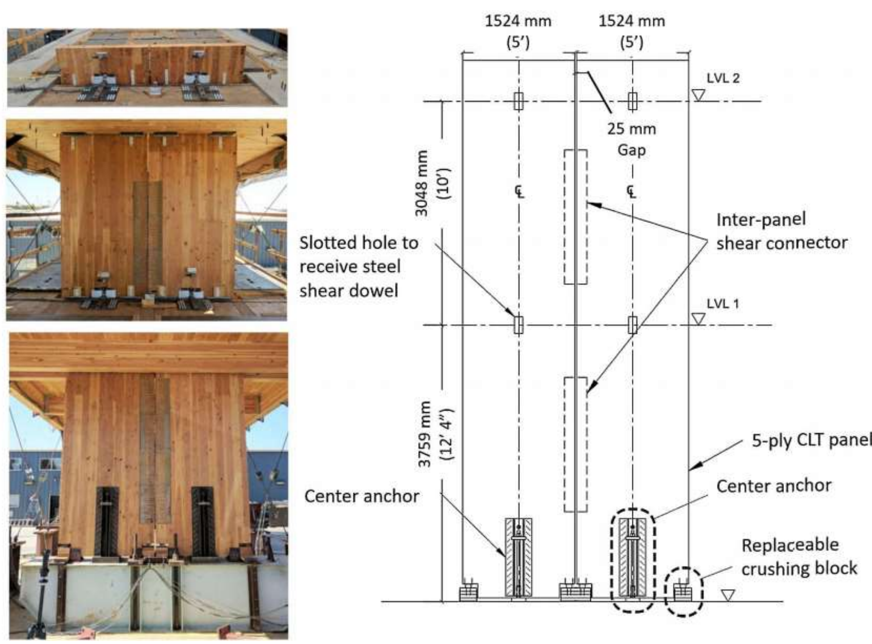

A) Base panel connections B) Close view of slip-friction connection

**Figure 3.8 Slip friction connection**

**Source: (Fitzgerald, 2019)**

*Interpanel Shear Connection*

Interpanel shear connection is a simple method of using coupled CLT rocking walls without post-tensioning.  Unlike other systems discussed, this connection system offers no self-centering capability. Blomgren et al. (2019) tested this system in a two-story balloon construction wood building. The building had a CLT floor with glulam beams and columns for the gravity system. A pin connection is provided at the base of the shear wall panels which allows rotation and acts as a hold-down (Figure 3.9). Shear load is introduced to the panels via a shear key at each of the two diaphragms. The bottom corners of the panel are cut out to allow for the installation of a crushing block. The crushing blocks transfer corner bearing of the panels in rocking motion. When bearing loads are high enough, the blocks crush under the weight to dissipate energy. The key of this system lies in the interpanel shear connection. This metal plate with long slots was designed by Katerra Engineering and used to connect two CLT panels (Figure 3.10).




A) Picture of system B) Diagram of system

**Figure 3.9 Interpanel shear connection LFRS**
**Source: (Blomgren et al., 2019)**

The system has two primary structural fuses. When the building faces a service level earthquake, the crushing blocks and interpanel shear connection should remain elastic and suffer no permanent deformation. However, when the building faces maximum considered earthquakes, the blocks crush, and the shear plate yields. Every other connection/connector is to remain elastic throughout these events. Tests concluded that damage was observed only in the intended structural fuses and the system met design performance expectations (Blomgren et al., 2019).

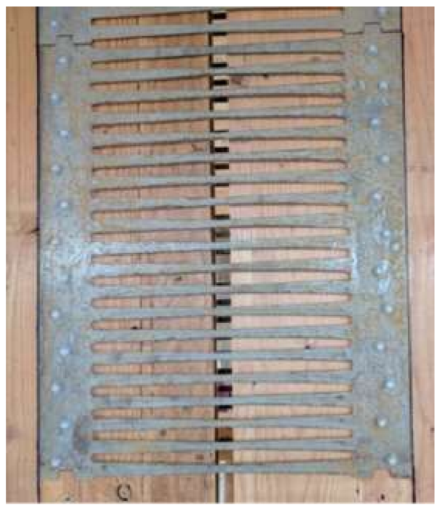


**Figure 3.10 Interpanel shear connection plate**
**Source: (Blomgren et al., 2019)**

### Implementation of Connection Systems

Unlike traditional CLT shear wall connection systems, implementation of rocking wall systems will follow performance based seismic design which requires accurate modeling of the system. Several researchers created models that have been calibrated to test results. After adequate testing, these models will help engineers correctly understand and analyze the seismic behavior of the building and implement it into design.

# Chapter 4 - Experimental Studies on CLT Shear Wall Buildings

## Introduction

The CLT shear wall systems are not commonly used for seismic applications currently. Investigation of the performance of these systems is ongoing. Due to the lack of code provisions and design guides, many CLT designers have opted to use other LFRS in seismic regions. Some large-scale tests of CLT LFRS for seismic applications have been conducted, which may lead to code adoption and more implementation of the systems. The following section describes some of the major projects conducted in order to better understand CLT LFRS.

## SOFIE Project

The SOFIE project (Ceccotti et al., 2013) consists of many tests including a seven-story full-scale shake table test on a CLT building with shear walls. The project was conducted by Tree and Timber Institute – Italian National Research Council and supported by Trento Province, Italy partnering with Shizuoka University in Japan. The project goal is to better understand the seismic behavior of CLT buildings which is considered a prerequisite for using this system in high seismic regions such as Italy.

Before erection of the large CLT buildings, a series of monotonic and cyclic tests were carried out on various panel joints, shear walls with openings and vertical loads. By understanding the connections first, the CLT building would be better optimized for the full-scale test (Ceccotti et al., 2013). Based on a previous shake table test for a three-story CLT building (Ceccotti, 2008), the SOFIE project incorporated information to better predict and design the large test building. In the previous test of the three-story structure, it was found that commercial hold-downs were not capable of handling the slender structure’s uplift forces.

Therefore, special high-strength IVALSA hold-downs were designed for higher uplift forces. In preparation for the tests, the seven-story project was designed with two critical connection locations in mind, the panel-to-diaphragm connection, and perpendicular panel-to-panel joints at the corners of the building. Special attention was given to these joints including connecting hold-downs between stories with metal rods. The panel-to-diaphragm connection was designed to be rigid. Overturning resistance is handled in the hold-down and nailed-in brackets transfer the shear between panel and diaphragm.


A) Test building

B) Additional steel plates for added load

**Figure 4.1 SOFIE test pictures**
**Source: (Ceccotti et al, 2013)**

This study also addressed the ductility capacity of parallel panel-to-panel connections. The vertical joint consisted of a surface spline with STS. As can be seen in Figure 4.1B, additional dead load was added to the structure in the form of steel plates to represent an operational building. After inducing 10 major earthquakes onto the structure, the building saw no residual displacement. The damage in the system was seen through nail pull-out in shear brackets and loosening of the connection of hold-downs through the diaphragm. Damage to the connections were reparable when connections are accessible. The response of the structure showed high accelerations and it was proposed the introduce more ductility and energy dissipation into the system to reduce the acceleration. Overall, the building displayed the capability of CLT to be used in high seismic regions.

## NHERI Projects

The Natural Hazards Engineering Research Infrastructure (NHERI) facilitated several two-story mass-timber shake table tests at the University of California, San Diego (UCSD) to better understand the LFRS behavior of several different CLT shear wall configurations (van de Lindt et al., 2019). The outdoor testing facility consists of a 25 ft x 40 ft uniaxial shaking table (Figure 4.2). In these experiments, the structure's gravity system consisted of glulam beams and columns and CLT diaphragms for the floor and roof. Different shear walls were tested including non-load bearing and load bearing. The building's footprint was longer in the N-S direction than the E-W direction in which the ground motion was applied. Two shear walls were installed for resisting E-W applied shaking. A variety of different CLT shear wall systems were tested, and several earthquake ground motions were simulated at varying intensities by the shaking table. Seismic performance of different systems is introduced as the following.


**Figure 4.2 NHERI Shake Table**
**Source: (Pei et al., 2019)**

## Conventional Platform CLT Shear Wall

A team of researchers, in an effort to establish seismic design parameters of conventional CLT shear walls, used the NHERI shake table to test the system (van de Lindt et al., 2019). The structure was designed for and R-factor of 4 using the equivalent lateral force procedure outlined in the ASCE/SEI 7-16. The system tested included anchor tie-down systems (ATS) in the edges of the shear walls to resist overturning and nailed-in shear brackets to transfer the shear load. Vertical joints were simple metal plates with nailed in connections. The shake table recreated some of the 1989 Loma Prieta earthquake records with varying intensities that correspond to a service level earthquake (SLE), design basis earthquake (DBE), and maximum considered earthquake (MCE). The spectral accelerations range from 0.52g to 1.5g. During SLE and DBE intensities, the system showed no observable damage in the connections. At MCE intensity, tie-down rods began to experience yielding, yet the structure was not close to collapse during this intensity and provided life safety. This study also concluded aspect ratio of the panel governs rocking or sliding motion. The study met its goal of providing useful information for the development of ELFP, providing insight into the performance of panel aspect ratio, and transverse walls do not inhibit the rocking motion of panels (van de Lindt et al., 2019).

### PT Rocking Wall

Rocking CLT shear walls with post-tensioning and U-shaped flexural plates were tested using the same testing facility (Pei et al., 2019). Much of this system has already been described in Chapter 3. The gravity system was of CLT floors and glulam beams and columns. Therefore, at each story of the structure, shear keys were developed to transfer lateral loads only. The PT enabled self-centering capabilities of the wall. Energy dissipation of the system was developed through U-shaped flexural plates. The test structure was subjected to 14 earthquake excitations based on a location in San Francisco to test SLE, DBE, and MCE earthquakes. SLE represented 50% probability of exceedance, DBE represented 10% probability of exceedance, and MCE represented 2% probability of exceedance in the next 50 years. The performance of the system is summarized as follows. No repairs required for SLE and DBE earthquakes and only required retensioning of PT bars in MCE level test. Minor damage was observed in the panel corners from the rocking motion generated by DBE and MCE ground motions, but no repair was required. The design of the shear key used in the project behaved as intended. In conclusion, the testing at NHERI achieved its goal of creating a resilient LFRS that sustains no major damage in all ground motion intensity levels. The two-story analysis will likely further research into taller rocking wall structure tests (Pei et al., 2019).

### Non-PT Rocking Wall

The non-post tensioned CLT rocking wall at NHERI offered important information on a new innovative approach to rocking walls (Blomgren et al., 2019). As explained in Chapter 3, the system uses an interpanel metal shear plate that is designed to be elastic under service level conditions and to yield in DBE and MCE events. Additionally, wood crushing blocks on the corners of the shear panels offer additional energy dissipation. The bases of the panels were connected to the foundation via a pin connection that kept the panels in the correct location. Testing procedure subjected the system to 13 earthquake motions based on ground motion records from historical earthquakes. Intensity levels of earthquakes range from SLE to 1.2 times MCE events on seismic hazard near Seattle, and San Francisco. The project objectives were to have no permanent deformations at SLE and DBE, and a max residual story drift of 0.5% for MCE events. After 13 earthquake excitations, these project objects were achieved by the system (Blomgren et al., 2019). After larger earthquake excitations, assessment of damage showed that damage was isolated to the intended structural fuses. Repair work conducted quickly and efficiently after the large earthquakes. The NHERI shake table tests at University of California, San Diego showed this system is capable of performing in mid- to low-rise structures. Further investigation is needed to determine the performance of the LFRS for higher buildings.

# Chapter 5 - Conclusion

The intention of this report is to review the state-of-the-art CLT shear wall systems and their connections for seismic applications. CLT panels offer several advantages that have promoted their growth in the past few decades. A current limitation for CLT buildings is the lack of understanding of CLT shear walls under seismic loads. Because shear wall panels behave almost rigidly to in-plane force, important characteristics in seismic systems such as ductility, deformation capacity, and energy dissipation must be generated in the connection systems. First, general connections were explained for the various scenarios within CLT framing. By observing some of the industry standards of connections such as the use of splines, half-laps, butt joints, brackets, STS and various other connection types, a basis of knowledge is formed for understanding CLT shear wall connections.

CLT shear wall systems are categorized into conventional shear walls and rocking walls. Conventional shear walls use similar connection systems established in shear walls of light-wood framing. Brackets and hold-downs are used to connect the panel to the foundation/diaphragm. It has been found in several studies that hold-downs improve the seismic performance of the shear wall systems. Additionally, the aspect ratio of the panel dominates the panels deformation between rocking and sliding. Rocking deformation is more beneficial to the performance of the shear wall. Thus, panels with higher aspect ratios can have better seismic performance. Higher aspect ratio panels are most practical in a multi-panel shear wall. Instead of a single panel, multiple panels can be combined using vertical joints to engage coupling action between panels in the shear wall. Testing shows that when properly designed, multi-panel shear walls improve the ductility, energy dissipation, and deformation capacity of the panels, allowing them to perform better under seismic loading. The important connection in the multi-panel shear wall is the vertical joint between panels. Spline joints, half-lap, and butt joints have been studied for this vertical joint. It is shown through several studies that connector orientation can have large effects on the behavior of the connection. The use of STS in shear creates ductile connections, while the use of STS in withdrawal leads to stiffer connections. The prescribed use of the shear wall may require a combination of both in order to generate the desired behavior of the shear wall. Currently, there is an effort within the research community to develop seismic design factors to help engineers design conventional CLT shear walls in areas governed by seismic demands.

CLT rocking walls approach earthquake response in an innovative manner. The concept of rocking walls is that the panel is designed specifically to rotate about its base under lateral loading. The freedom of movement allows force to be redirected into structural fuses in the connection system. Rocking walls can be divided into post-tensioned and non-post-tensioned shear walls. Post-tensioned shear walls rely on steel rods to self-center the walls during rocking motion. Energy dissipation is introduced into the system through means of U-shaped flexural plates, energy dissipators, and coupling beams. Non-post-tensioned rocking walls rely on alternative methods to re-center the panel or may neglect self-centering entirely. These systems include slip friction hold-downs or inter-panel shear plates to dissipate energy. Rocking wall systems attempt to create a strong structure during frequent earthquakes, and resilient and robust systems during large seismic events. Many of these systems allow for easy repair of connection components after a major earthquake. In all systems, favorable seismic characteristics such as ductility and energy dissipation were created from the connection systems.

Finally, some recent experimental studies were presented in which large scale building models were tested statically and dynamically. This includes the SOFIE project with a large seven-story full scale CLT building in a shake table test. Moreover, the NHERI UCSD shake table tested several different orientations of shear walls in two-story building model. Together, these studies show the inherent strength that can be achieved with CLT shear walls. All of these studies were successful in meeting the project goal of life safety in MCE levels. There were additional project goals including limiting deformation, ease of replacing components, and damage limited to structural fuses. Each of the projects met their perspective objectives.

Continued research and understanding of CLT shear walls in seismic applications will allow for more implementations of this building material. CLT projects have seen tremendous growth in non-seismic regions. Currently, CLT structures with concrete or steel LFRS are built in seismic regions. Through further research of connections in seismic applications, CLT structures with CLT LFRS can be used in seismic regions. Using CLT as the entire structural skeleton for the building optimizes the construction and design of the project. Less coordination between disciplines allows for faster and more efficient construction and eliminates the detailing considerations for combining two separate materials. CLT construction has and will continue to grow. The research of CLT shear wall connections will allow CLT buildings with CLT LFRS to be built in seismic regions.

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