Innovations in mass timber lateral systems

by

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Abstract

As mass timber becomes increasingly popular in the United States and around the world, there comes more demand for mass timber in larger buildings. With this demand comes a necessity for these buildings to be able to withstand seismic forces; and in some locations, these forces can get quite high. Typical mass timber lateral systems (such as CLT shear walls) have worked fine for lower seismic forces and shorter buildings, but with this new demand comes a need for newer systems. Rocking timber walls is one of these systems. The goal of rocking timber walls is to allow the lateral wall system to move in the case of high seismic force, thus reducing the load the wall undergoes. This is done with vertical post tensioning (PT) within cross-laminated timber panels (CLT). In addition, easily replaceable energy dissipation devices, such as U-shaped flexural plates (UFPs), allow for concentration of inelastic deformation during rocking of the walls, which keeps the CLT and PT components free from harm. Another system used to handle seismic load in tall mass timber structures are inter-story isolation systems. These systems can isolate the force at separate levels, effectively decreasing the load the foundation takes from the building's movement. Even newer than these systems is the Floor Isolated Re-centering Modular Construction System (FIRMOC), which utilizes rocking timber walls, inter-story isolation, and the addition of prefabricated modular mass timber to create a system capable of effectively and efficiently dealing with large seismic forces. This report seeks to present these innovative, capable, and effective lateral systems for seismic forces in large scale mass timber structures in a manner that provides understanding of how they work and what makes them effective.

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Chapter 1: Introduction

Mass timber is an emerging building material in large scale multi-story buildings. Wood use is common for small scale residential structures; however, this use of stick frame members is not sufficient for larger buildings with high loads. Mass timber solves this by creating larger members that can sustain these loads, such as Cross-Laminated Timber and Glue-Laminated Timber. Wood is a sustainable and renewable resource. With increasing consideration for the environment there is a larger push for utilization of wood products in building design. Wood is already quite common for use in small scale residential buildings, but the wood used in those applications is not applicable for large scale buildings. This is due to strength limitations as well as inadequate fire resistance. Mass timber has the strength and other properties suitable for mid-rise to high-rise construction.

Mass timber also brings other benefits. For one, wood is significantly lighter than concrete, which can help with ease of construction. In terms of another environmental benefit, mass timber buildings actively participate in an action labeled "carbon sequestering". Carbon sequestering means that the timber stores carbon within its structure, ultimately leaving a negative carbon imprint throughout its lifespan (Ahmed et. al. 2020). A key benefit, and the largest reason for its increasing popularity, is due to its aesthetic appeal. Wood, being a natural resource, is a lot more visually pleasing. Architects often like to highlight the inherent beauty of wood in buildings that utilize it.

While there are benefits to mass timber, it comes with its share of disadvantages as well. A common misconception when considering mass timber construction is that a mass timber structure would be lighter than a steel structure. While wood as a material is lighter than steel, steel is a much denser and stronger material. This means that with a given load, an adequate steel member for that load would be lighter than an adequate timber member for that same load. Another disadvantage that comes with mass timber is the lack of code and understanding for mass timber in mid to high-rise buildings. While research has started building over the past decade, the collective understanding of how mass timber operates is nowhere near that of steel and concrete. This is the most pressing disadvantage for mass timber and is the main setback preventing its widespread use.

Cross-Laminated Timber (CLT)

Mass timber comes in a variety of forms. The most common of which are Cross-Laminated Timber (CLT) and Glue-Laminated Timber (Glulam), but there is also the less common but still applicable Dowel-Laminated Timber (DLT) and Nail-Laminated Timber (NLT). This report focuses on Cross-Laminated Timber.

CLT consists of layers of dimensional lumber laid perpendicular to each other, then glued together. See Figure 1. This forms a single structural panel, whose strength enables longer spans than dimensional lumber. Typically, CLT panels contain anywhere from three to seven layers of ⅝” to 2” thick dimensional lumber. These plies are then glued together with melamine, polyurethane, and phenolic based adhesives. Ideally, timber beams and columns could be cut from a single tree, without the need for multiple members to be glued together. This is possible only in smaller structures, and companies such as WholeTrees structures are founded on that idea. However, for larger scale structures, this is not realistically or financially feasible. CLT and other types of mass timber products were created to allow stronger wood members to be used in design without the need for large trees, which take significantly longer to produce. (Ahmed et. al. 2020)

Figure 1: Cross-Laminated Tiber (CLT)

Source: (APA 2018)

CLT is a relatively new material, being first introduced in the early 1990’s in Austria and Germany. Though it wasn’t until the early 2000’s that it started to pick up popularity, initially in Europe then a bit later in North America. In addition to the increasing desire for environmentally friendly ‘green’ buildings, CLT also grew in construction due to effective marketing campaigns and improved distribution channels. While CLT has become fairly established within European countries, its use in North America is still trying to find similar foot holding. A large reason for this is the need for more resilient seismic design in North America compared to Europe, as well as limitations in established code. (Austin 2020)

CLT in the United States

Over the past few decades, Europe and Canada have seen a substantial increase in the research and use of mass timber. The Canadian Wood Council (CWC) is largely responsible for current design code for mass timber in North American commercial use. Despite its increasing popularity outside of the United States, the US has not followed suit. Or rather, they are further behind in the process.

CLT was first introduced into North America in the early 2000's. Since then, there has been some effort to produce exploratory building projects in Canada and the U.S. using CLT, despite limitations on supply, structural safety, and serviceability. Structurlam and Nordic Structures, two companies formed around 2010 with the purpose of producing local lumber for CLT panels, have been the prominent source of CLT for Canada. More recently, the Montana based company SmartLAM which was formed around 2012 became the first CLT company in the U.S. (Ahmed et. al. 2020).

In Europe, CLT panel mechanical properties have been determined on an individual basis by CLT manufacturers. However, in North America, through the combined efforts of the ANSI (American National Standards Institute) and APA-The Engineered Wood Association, a CLT material standard was developed based on performance (Yeh et al. 2012). This standard, the ANSI/APA PRG 320 *Standard for Performance Rated Cross Laminated Timber*, has slowly been adopted by CLT manufacturers in North America, including the previously mentioned Structurlam. FPInnovations created a design handbook for timber building (Canadian CLT Handbook), in addition to other design handbooks being created by other sources (such as the Mass Timber Design Manual by ThinkWood). These developments have been key in the growth of mass timber in Canada but have also significantly contributed to growth within the United States (Ahmed et. al. 2020).

While the US is lagging in the research and implementation of CLT, there are active efforts being made to further our understanding of CLT. In November of 2015, a mass timber research workshop was held in Madison, WI. This was hosted by the United States Department of Agriculture (USDA) Forest Service, Forest Products Laboratory (FPL), and Softwood Lumber Board, and over 125 representatives from major research projects related to mass timber attended with the purpose of discussing the current status and future direction of North American CLT research (Pei et. al. 2016).

The movement into necessity of CLT seismic resistance

Initially, CLT was used only for floor panels and load bearing walls. The rigidity and inherent strength of CLT paired well with these applications, and it allowed for wood to be integrated into a large portion of the structure. In these cases, a conventional lateral force resisting system would be used in the structure, often steel braced or moment frames, or concrete or masonry shear walls. It was not until recent years that CLT began being used for the lateral system as well, allowing for an entire building structural system to be made from mass timber. The opportunity for this new application became available with the increase in research of mass timber.

Mainly this increase in research provides a better understanding of how CLT lateral systems operate under seismic loading. Many of the seismic studies on CLT structures were focused on connections, monolithic and segmented wall systems, and full-scale buildings. CLT lateral structural systems, most commonly in the form of CLT shear walls, rely heavily on connections. CLT lacks ductility under cyclic loading, which is a large drawback for CLT use in mid-rise or high-rise buildings in high seismic areas. In conventional CLT shear walls, the main approach to dealing with seismic lies within connections, mainly brackets and hold-downs, that counter the force applied. However, with increased seismic loading, this may not suffice, creating a need for more innovative solutions for mass timber lateral systems in order to deal with seismic loading.

Structure of the report

This report seeks to provide an overview of how CLT is currently being used in seismic applications and what innovations are being pursued to overcome the flaws in current CLT lateral systemsFirst, common practices are introduced for non-mass timber lateral systems. Currently applicable CLT lateral systems are explained along with how they operate and the variability in the individual parts of their systems. Then, new and innovative systems are discussed, with an explanation for how they work and the ways in which they overcome the shortcomings of the current systems. Finally, emphasis is made on the necessity of continued innovations in mass timber lateral systems and their implementations in order to further the applicable reach of timber structures in the United States and around the world.

It is important to note that the IBC 2018, referencing the ASCE 7-10 Table 12.2-1, limits timber shear walls to 65’ structures in seismic design category D. This report looks into systems that are viable at this height but could also allow for taller heights in this seismic design category. Looking into these systems could hopefully allow for taller building limits in future codes.

Chapter 2: Current CLT Lateral Systems

All buildings are designed to withstand two fundamental types of forces: gravity forces and lateral loads. Gravity forces (such as building self-weight and the weight of the people within it) are resisted by slabs, beams, columns, and occasionally load bearing walls, which are parts of gravity force resisting systems. The lateral forces are resisted by shear walls, braced frames, or moment frames, which are lateral force resisting systems. For most buildings, lateral loads come from two main sources: wind and seismic. While wind acts as a static load, earthquakes act as a dynamic load. While using the equivalent lateral force procedure designs for seismic as a static load, the dynamic nature of earthquakesstill causes complications lateral members. Buildings under high seismic loading need increased ductility in order to minimize damage of the structural system. This ductility is less important in buildings designed for wind.

When designing a structure to resist seismic loading, there is a minimum design standard referred to as life safety. This means designing with the purpose of preventing collapse until all occupants can safely exit the building, even in high seismic occurrences. This can be met in a number of ways, including but not limited to a strong and stiff lateral system to resist any and all movement of the building elastically, a ductile lateral system that allows some yielding in the structure without collapse, or isolating the seismic motions of the ground to prevent them from being applied to the main structure through a base isolation system.

Buildings can also be designed to go above and beyond this minimum standard of design, in order to prevent severe damage to the building even under major earthquakes. While doing this may cost significantly more up front, it could save the building from being lost altogether should there be a rare earthquake event. Also, money could be saved in the long run through minimal or decreased cost of repairs compared to a less durable system.

Regardless of whether the governing loading case is wind or seismic, a lateral system must be implemented in order to resist those forces. For most buildings, one of three systems can be chosen for this task: braced frames, moment frames, or shear walls.

Most common in steel construction, though possible for mass timber, braced frames consist of angled bracing between columns used to resist lateral loading. The bracing itself can be laid out in a few different ways, such as X-bracing, diagonal bracing, and V- or inverted V-bracing.

Moment frames resist horizontal forces through rigid (moment) connections between columns and beams/girders. In order to achieve the necessary strength and stiffness, member sizes for the columns and beams are often larger than they would be in a braced frame resisting the same forces. The main purpose of utilizing moment frames over braced frames is to provide more flexibility for the architects, such as allowing larger openings for architectural appeal, allowing for more windows or other such aesthetics.

While braced and moment frames are common among steel structures, shear walls are more common with the use of concrete and masonry. A shear wall in these cases is a reinforced concrete (or masonry) wall designed to withstand lateral loading. Shear walls provide a large amount of strength and stiffness for the rest of the structure, compared to frames of similar dimensions. In addition, shear walls can be designed with openings as well, so windows and doors could also be reasonably implemented into shear walls.

CLT Shear Walls

When looking at CLT as a material for the lateral force resisting system, there is currently only one leading option: shear walls. With CLT panels being a 2D element, this is the most effective use for them in a lateral system. Traditionally CLT panels have been used as floor slabs, with steel and concrete or masonry lateral systems. However, with the push for increased utilization of mass timber in taller structures and higher seismic areas, CLT shear walls have begun to attract more attention. Since the CLT wall panels are rigid, they work well to provide the necessary strength and stiffness for a shear wall, especially when wind load governs. However, the rigidity of these panels means they lack the ductility and energy dissipation that are needed for adequate lateral resistance under seismic loading. In response to these shortcomings, the connections of the CLT shear walls are designed to provide the necessary ductility and energy dissipation. In some cases, additional attachments precisely named 'energy dissipation devices', will be used to provide adequate energy dissipation.

Since the connections are the main elements providing ductility and energy dissipation, the connection system chosen will have a big impact on the overall performance of the lateral force resisting system (LFRS).

CLT Shear Wall Connection System

While CLT shear walls are still relatively new, they have been used in some building applications. Studies have been conducted to investigate the seismic behavior of CLT shear walls in order to prequalify it in building codes. Due to their unique characteristics, there are three factors that impact its strength and ductility: the connection type, the connectors, and the construction type.

A typical CLT shear wall consists of two to three main parts: The CLT shear wall panel(s), the horizontal connections (which occurs at the panel-to-foundation and panel-to-diaphragm locations), and the vertical panel joints. Vertical panel joints are used to connect two shear wall panels together in coupled shear walls, so in single panel shear walls there will not be vertical joints. CLT shear walls can easily resist the story shear due to their inherent strength and rigidity. The connections will fail before the CLT panel. There are two main components for typical CLT shear wall horizontal connections: brackets and hold-downs, which are shown in Figure 2. Hold-downs are located at the edge of the panel and resist overturning moment. Brackets are placed between the hold-downs and vary in quantity and complexity based on loading requirements. The purpose of the brackets is to transfer the shear to the foundation or to the story below. Both brackets and hold-downs can be connected using a variety of fasteners (connectors), commonly nails or screws.

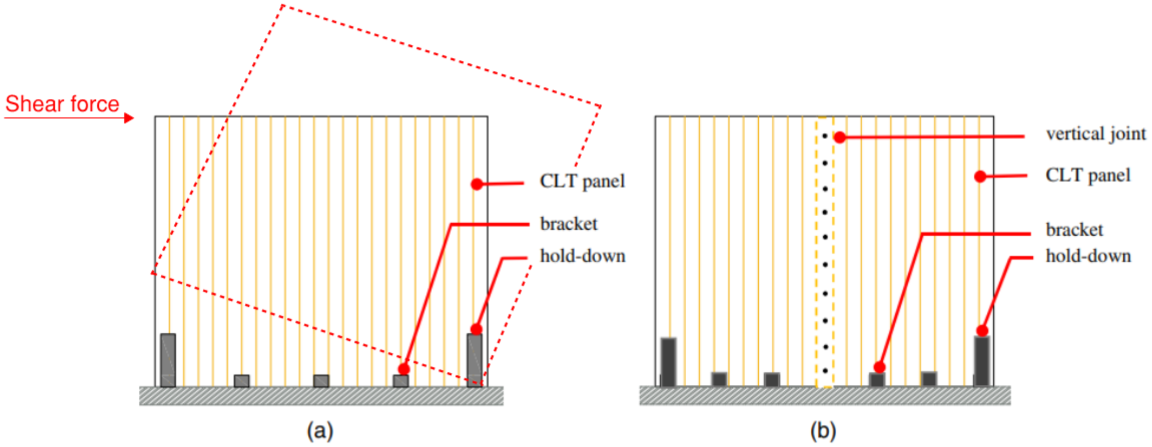

Figure 2: Components of (a) single; and (b) coupled CLT shear wall

Connection Type

It is important to understand the varying forms of connections, as they play a large role in the strength of the shear wall. Anchor tie-down systems are a common option for the hold-down connection. In this system, continuous steel rods on the edges of the shear wall work as the connection from the panel to the diaphragm, and they also provide overturning resistance. Toe-screwing is another viable hold-down option. However, due to its lack of energy dissipation and overturning resistance, it perhaps should not be the first choice for high seismic regions. As seen in Figure 3, a hold-down can also consist of a long bracket.

Figure 3: Brackets and Hold-downs

Source: (Sandoli et. al. 2021)

Metal brackets, often used in conjunction with anchor tie-downs, act to transfer the shear from the panel above to the panel below in platform construction. In balloon type construction, shear is transferred between the panel and the foundation. These construction types are discussed later. In addition, brackets act to connect the shear wall to the diaphragm/foundation. While a shear wall could operate sufficiently with just anchor tie downs or just metal brackets, using both together allows for the strengths of both (overturning resistance and shear transfer) to be gained by the system. Therefore, typical shear walls include these two connections. Variation in brackets comes down to shape and size. Larger brackets would be needed where larger shear transfer is required.

Vertical Connections occur between shear wall members in both platform and balloon type construction, but only with the use of multi-panel shear walls. Multi-panel shear walls consist of two or more panels connected through vertical joints. These vertical joints add additional ductility on top of the panel-diaphragm/foundation connections that are present in single-panel shear walls. A single-panel shear wall is one panel, either at each floor (platform type construction) or that runs through the height of the building (balloon type construction). In this case, ductility behavior must come solely from the panel-to-diaphragm and panel-to-foundation connections. Multi-panel shear walls, when designed effectively, can also add deformation capacity to the panels.

There are a variety of options for these vertical connections such as self-tapping screws, internal splines, single surface splines, double surface splines, and half lap joints to name a few. However, as this report does not focus on multi-panel shear wall applications, these connections are not discussed in depth.

Connectors

All connections must utilize connectors. Metal brackets provide no support without a connector applying it to the wall panel. There are a variety of options when it comes to choosing a connector, and the main points of consideration are strength of the connector and ease of utilization.

The most common choice of connectors for CLT are self-tapping screws, but nails, bolts, and dowels (as show in figure 4) will also work. An advantage of wood self-tapping screws is their ability to take combined axial and lateral loading. This is largely due to their high lateral and withdrawal capacity. Self-tapping screws are also relatively easy to install, since pre-drilled holes are not required.

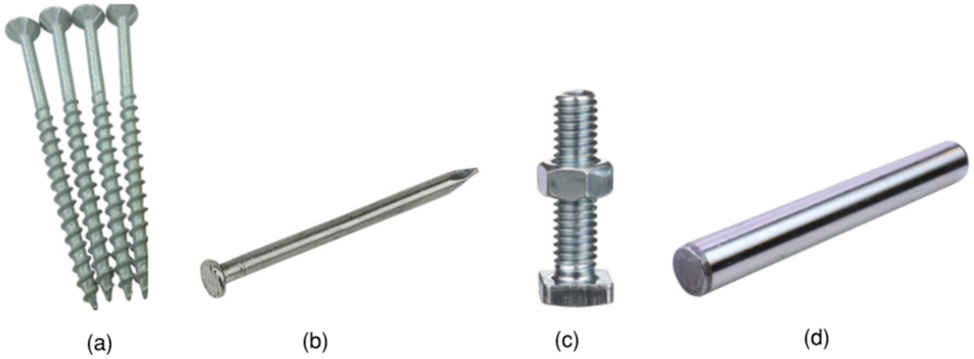

Figure 4: Connectors - (a) Self Tapping Screw, (b) Nail, (c) Bolt, (d) Dowel

Source: (a): (Your Choice Fasteners and Tools CO, LDT 2019), (b & c): (Walmart 2022), (d): (UTURN Fasteners 2022)

Self-tapping screws can also be used as the hold-down connection. For them to be used for this, the process of toe screwing must be utilized. Toe screwing involves inserting the self-tapping screws diagonally at the edge of the panel. There is concern for its strength and effectiveness for lateral loading (Popovski & Karacabeyli, 2012). For this reason, they are often not suitable for walls subjected to high wind or seismic, and therefore are not a good option for connecting walls that include a CLT shear wall panel. However, in areas or structures where lateral loading is minimal, this is a sufficient option.

Use of nails is far less common in CLT panels than screws. Nail connections in the end grain of CLT panels (and wood products in general) do not provide adequate resistance for withdrawal forces or lateral forces. For this reason, many timber design codes prohibit the design of nailed connections for withdrawal forces, and they provide an end grain factor for nailed connections designed for lateral resistance. In mass timber construction, bolts and dowels are extremely common, including for use in CLT shear panels. While bearing-type fasteners can and have been used for other mass timber product connections (such as glulam), they are not frequently used for CLT panels.

Construction Type

For multi-story buildings, there are two main construction approaches which will affect the design of the CLT shear wall: platform type construction and balloon type construction.

Platform construction breaks up the CLT shear wall into individual panels at floor levels. This can be seen in Figure 5. The base shear wall is connected to the foundation as usual, but the panel stops at the first-floor diaphragm. This base panel is then connected to the diaphragm above using brackets or self-tapping screws as previous mentioned. Then, the next CLT panel is placed on top of the diaphragm and is connected using a combination of brackets and hold-

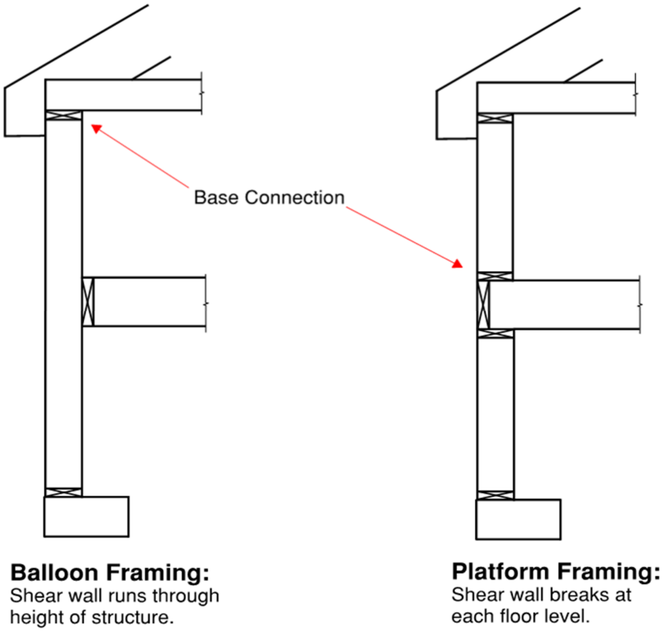

Figure 5: Balloon vs Platform Type Construction Framing

downs. The brackets at each level now transfer the story shear to the floor below, and the shear loading accumulates as it moves down the building. Overturning occurs at each level and must be resisted by hold-downs. In platform construction, each story has an independent shear wall system that transfers its force to the story below. One issue that comes with CLT platform construction is the loading that the shear walls impose to the diaphragms (CLT floor panels), mainly compression stresses perpendicular to the grain. This compression can be difficult to design for.

Balloon type construction takes a different approach, with the shear wall being continuous through the height of the structure. The continuous wall panel, braced at each story by the diaphragm, is connected to the foundation using brackets to transfer the shear and hold-downs to resist overturning. So, the quantity of connections required drastically decreases as there is no longer a need for brackets at each level to transfer the shear from story to story. Also, there is no need for hold-downs at each floor. However, the connections between diaphragms and shear wall panels need to transfer the lateral loads at each floor level. Another benefit that comes with balloon type construction is the elimination of compression perpendicular to grain stresses as mentioned in platform type construction.

Summary

Current CLT lateral systems are limited to shear walls, where strength of the system relies heavily on the connections. Hold-downs are used to resist overturning of the panel, and brackets transfer shear to the foundation. Connectors such as self-tapping screws, nails, bolts, and dowels are used for these connections, and their strength must be considered in addition to the connection. Framing of a shear wall can be done in one of two ways, each influencing the connection system. With platform framing, hold-downs are required at each level since overturning occurs at every level. In addition, brackets are required at each level to transfer the shear from the panel above to the panel below. An issue that arises with platform framing is compression perpendicular to the grain that is imposed on the diaphragm. This issue can be solved using balloon framing. With balloon framing, hold-downs will only be at the foundation since there is only one shear wall panel which runs through the height of the building. Brackets will be located at the foundation as well as the roof. Balloon framing has its limits though, as a single shear wall panel cannot span many stories.

While there is variety for current CLT lateral systems in the form of connections, connectors, and construction type, they are still limited in scope. Typical brackets and hold-downs (along with their connectors) handle high seismic loading poorly, lacking sufficient ductility and strength. In order to provide accessibility for complete mass timber buildings under high seismic load conditions, new innovative systems must be utilized.

Chapter 3: Innovative CLT Lateral Systems

Continual efforts are being made to further CLT applicability in high seismic regions. Much of this focus is on studying and testing innovative systems. This chapter provides an introduction of some of these innovative systems, how they work, the variety of forms they can take, and how they can improve seismic performance. Three systems are discussed: rocking timber walls, inter-story isolation, and the Floor Isolated Re-centering Modular Construction System (FIRMOCs). The most prominent of these are rocking timber walls.

Rocking Timber Walls

Collapse due to seismic forces occurs because the ground motion of the earthquake exceeds the resistance of the structure. Structure will laterally deform until collapse occurs. Typical CLT shear walls account for this by attempting to prevent the motion altogether. The hold-down connections on the end prevent the shear wall from overturning by taking a large tension force. However, with taller buildings, this prevention becomes increasingly difficult. The more stories in the structure, the more the lateral loading accumulates through each level. This forces shear wall connections, specifically the hold-downs, to be extremely large. This can be impractical for constructability. The idea behind rocking timber walls is to allow some lateral motion within the walls in order to limit the connection strength required. In addition to allowing single plane motion, the system also includes re-centering of the wall. This is to ensure the shear walls will always rest in their original position after the ground motion subsides. The difference in rocking motion between a rocking timber wall and a traditional shear wall is show in Figure 6.

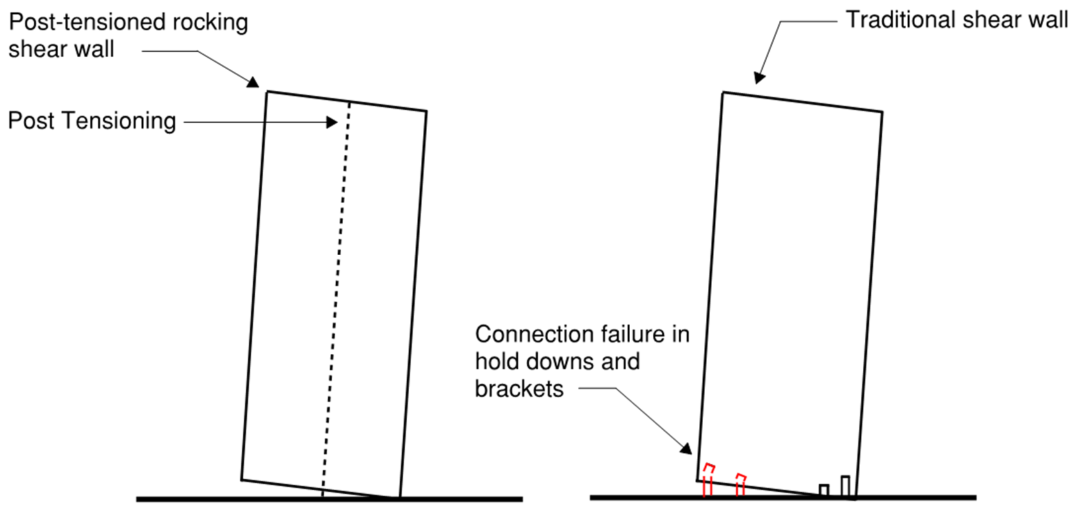

Figure 6: Rocking Motion in (a) PT Shear Wall and (b) Traditional Shear Wall

The goal of rocking timber walls is to utilize the key strength of CLT shear walls (rigidity) by forcing rigid body motion. Rocking timber walls, as the name suggests, allow CLT shear walls to ‘rock’ back and forth as a rigid body in the event of high seismic loading. Then, as the ground motion subsides, the wall re-centers itself into its original position. This is done through the connections. Currently, there are two main approaches to rocking timber wall design. One approach utilizes post tensioning for re-centering of the panel. The other system can provide re-centering without the use of post tensioning. These non-post-tensioned shear walls instead use connections known as resilient slip friction (RSF) joints.

Rocking timber walls were first introduced in New Zealand, with the innovative use of a post-tensioned mass timber system. This idea came from the use of post-tensioning in concrete (Buchanan et al. 2008). Since then, research has been done to further this idea, with the implementation of energy dissipation devices to localize damage away from the CLT panel, as well as a rocking timber wall system that does not require post tensioning.

Rocking Timber Walls with Post-Tensioning

A typical PT rocking timber wall consists of three main elements: the CLT shear wall panel, post-tensioned (PT) connections, and energy dissipation devices, as shown in Figure 7. Location and extent of application of both PT and energy dissipation devices can vary, but their purposes remain the same; the PT provides re-centering of the panel, and energy dissipation devices localize damage to themselves.

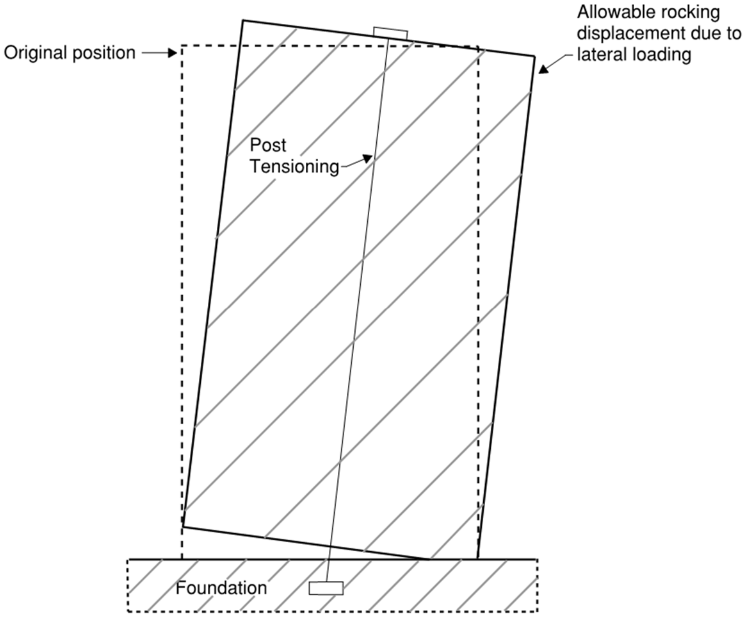

Figure 7: PT Rocking Timber Wall Elements

In a traditional shear wall system, failure occurs when the hold-downs fail. Shear wall panels are not allowed to rock prior to failure. However, with rocking timber walls this is not the case. With PT rocking timber walls, the PT is the element that allows rocking without failure.

The post tensioning rods or tendons in CLT shear walls run through the length of the panel and are anchored at the foundation and/or at each floor. While the CLT shear wall panel rocks, the PT rods or tendons will remain elastic through all loading. This is to ensure the post tensioning can provide the restoring moment for the CLT panel, pulling it back towards its original position, so that no residual drift would occur. The PT also creates a decompression moment. Rocking of the timber wall only occurs when the overturning moment by the lateral load is greater than this provided moment. The desired decompression moment for the PT is obtained through tensioning at the anchorage locations. Through this, the decompression moment can be increased or decreased depending on the need in design. Prior to loading exceeding the decompression moment, any lateral loading is withstood by the shear and flexural resistance of the CLT shear wall. In this stage, the shear wall acts just like a typical shear wall where movement is prevented, only allowing motion once the decompression moment is exceeded. These rocking walls in which PT is actively re-centering the wall in the event of seismic loading are also known as self-centering CLT walls (SC-CLT).

Not only does post tensioning act to provide self-centering capabilities, but it also acts as the replacement for hold-downs, which as mentioned before is a common connection for typical CLT shear walls. Hold-downs would normally be used as connections between the shear wall and the diaphragm or foundation, but with SC-CLT walls, the PT bars are anchored at those locations, acting as both the connection and re-centering system. Since the PT bars must remain elastic in order to accomplish self-centering, it is unable to provide any energy dissipation in a large seismic event. It is for this reason that energy dissipators are utilized, in order to make up for that.

Energy dissipation devices are used to localize failure in order to reduce damage of the shear wall panel and other components. Under high seismic loading, these devices dissipate energy, reducing force demand on the wall panel. This results in these devices experiencing the brunt of the load, meaning they are more susceptible to damage. This is also part of its purpose. Energy dissipation devices are often easy to replace, or at least easier than replacing an entire

CLT shear wall panel. By having these devices decrease the loading felt by the shear wall, and in turn failing first under high seismic loading, substantial damage can be avoided for these structures.

A common energy dissipation device used for these applications is a U-shaped flexural plate (UFP). This was introduced in 1972 by Kelly et al. with the purpose of easing seismic cyclic loading off connections and onto specialized devices. The UFP's were designed with the sole intention of dissipating energy. This idea was brought up well before rocking timber walls were created, yet they have become an essential aspect in many of their designs today. The good hysteretic behavior, as well as being relatively inexpensive to fabricate, have been large contributors to its popularity.

UFP's are formed by bending a heated steel plate section over a chosen diameter. This shape can be seen in Figure 8. The strength of these UFP's comes from their ability to have two malleable points of resistance under cyclic loading. When loading is experienced by one side of

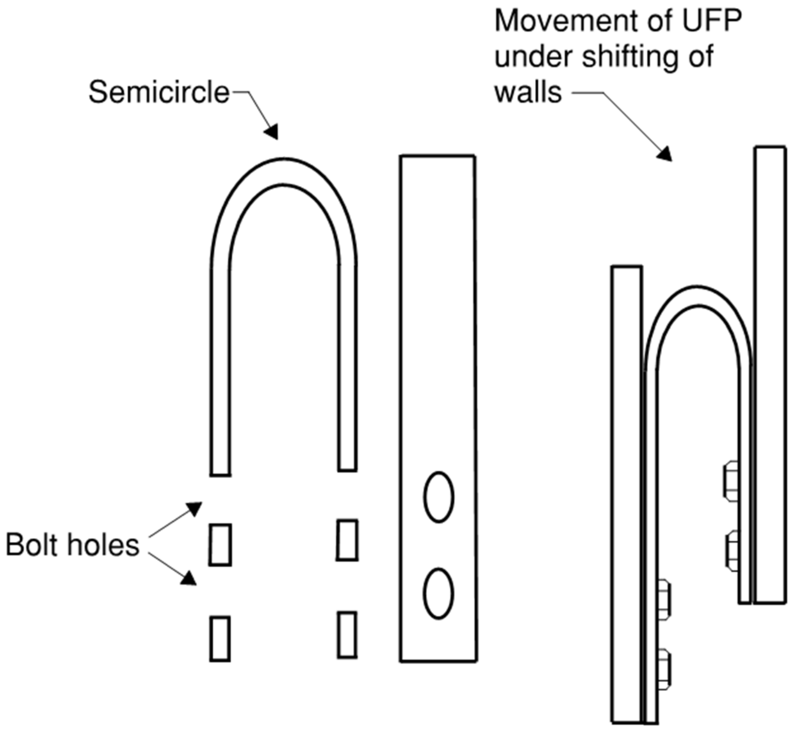

Figure 8: U-Shaped Flexural Plates

the plate, the half circle section rolls along the plate, providing the second point of resistance on the other side. Under cyclic seismic loading, this action moves back and forth, and it is this ability to roll that allows UFP's to perform well in seismic applications as energy dissipators (Baird et al. 2014). In the event of high seismic loading, these dissipators will fail first to prevent any damage from occurring in the shear wall panel prior to their failure.

UFP's are placed on the edges of the shear wall and connect to the adjacent columns. This is seen in Figure 9 (a). In multi-panel shear walls, the UFP's are placed between the two shear walls, with one straight side on each panel and the curved half circle spanning across the gap. This is seen in figure 9 (b).

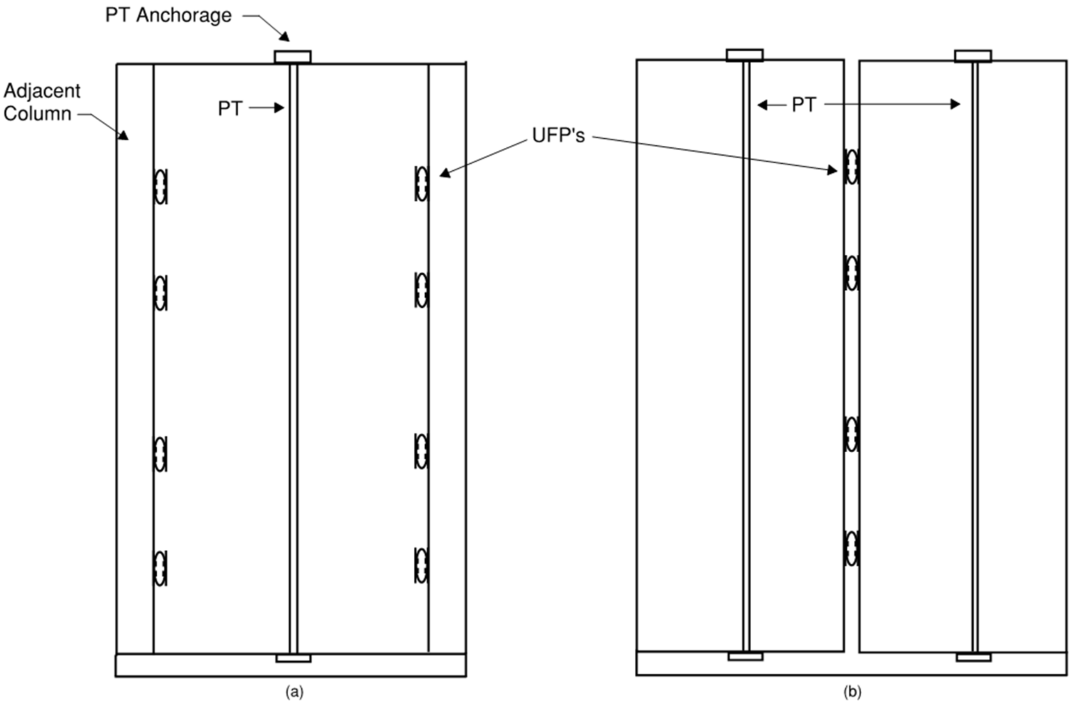

Figure 9: U-Shaped Flexural Plate (UFP) Application in (a) Single Panel Shear Walls and (b) Multi-Panel Shear Walls

Another energy dissipation device used in rocking timber walls are mild steel energy dissipators. See Figures 10 and 11. These are steel rods designed to yield in both tension and compression. Epoxy is put inside the rods in order to prevent compression buckling.

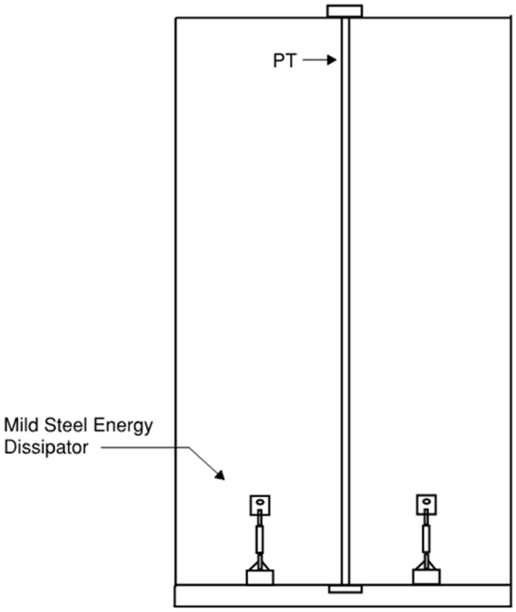

Figure 11: Mild Steel Energy Dissipator in a PT Rocking Timber Wall

Figure 10: Mild Steel Energy Dissipator

Source: (Iqbal et. al. 2010)

Rocking Timber Walls Without Post-Tensioning

Another approach to designing rocking timber walls removes the need for post-tensioning. Instead, slip friction joints are used. Slip friction joints replace the hold-downs in a typical shear wall system, being placed at the ends of the panel. Energy dissipation systems that are required for post tensioned CLT shear walls are designed to fail, so that the rest of the system suffers minimal damage. However, replacement of these devices can be costly. Also, there could be cases where the location of the energy dissipation device is difficult or impossible to access for repairs or replacements. Slip friction joints solve this issue by acting as a damage resistance energy dissipator. Unfortunately, typical slip friction joints will have residual drift following a seismic occurrence, meaning another system would need to be implemented for re-centering of the shear wall. This disadvantage makes a typical slip friction joint undesirable for use in rocking timber shear walls. That is where the use of innovative RSF joints comes in.

The RSF joint combines the hold-down connection and the energy dissipation device and puts them into a single system. Like a typical slip friction joint, the RSF continues to act as the resilient energy dissipation device for the system. However, the RSF configuration also provides re-centering for the shear wall.

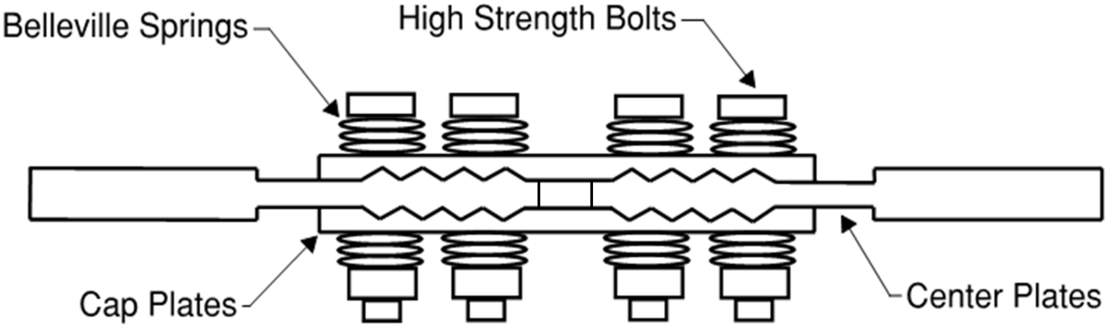

Figure 12: Resilient Slip Friction Joint (RSF)

As shown in Figure 12, a RSF joint consists of center plates sandwiched by grooved external cap plates which are connected through slots in the center plate using a combination of high strength bolts and Belleville springs. A Belleville spring is a disc spring that is specifically designed for bolts to prevent loosening caused by vibration. It is essential for the CLT shear walls under seismic action. The RSF is designed so that once the lateral force applied exceeds the frictional resistance between the cap plates and the center plate, the center plates will ‘slip’ allowing for energy to be dissipated through friction. Prior to this, the connection acts just like hold-downs in conventional CLT shear wall systems preventing motion of the panel. This idea directly matches that of post-tensioned rocking timber walls, where the decompression moment of the PT must be overcome before rocking occurs. The difference of the two systems mainly exists in energy dissipation. While rocking timber walls with PT require additional energy dissipation devices for energy dissipation, a RSF does so through friction and provides that in one system along with re-centering. The re-centering is possible through the shape of the grooves in the cap plates in combination with the Belleville springs. Conceptually, as the center plate slips, the springs are extended. The compaction of the spring pulls the plates back to their original position. It can do this since the compaction force for re-centering is greater than the frictional force of the plates that are resisting, as illustrated in Figure 13.

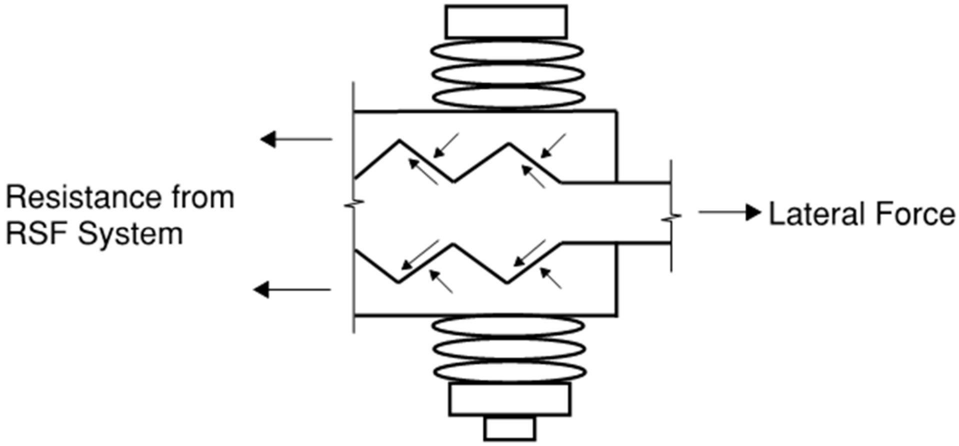

Figure 13: Resistance of Resilient Slip Friction Joint

The main purpose for the creation and use of RSF joints for CLT shear walls was to improve constructability, ease of repair, and lower the cost. The implementation of RSF connections takes away the need for additional energy dissipation devices within the wall, since that process is allocated to the RSF. In addition, the RSF is designed to resist damage from energy dissipation, whereas typical energy dissipation devices are designed to yield, requiring repair or replacement after significant seismic loading. Reducing the need for constant replacement and repair of key materials can substantially reduce cost throughout a building's life cycle. The implementation for RSF is also simple, being similar to hold-downs. Post-tensioned walls require steel bars to be inserted through the shear wall and tightened, as well as multiple placements of energy dissipation devices. The use of RSF makes construction quicker and simpler, which can also cut down overall construction time.

Inter-story Isolation System

Inter-story isolation is an innovative concept that has been applied to both steel and concrete buildings for practical use (Mele & Faiella 2018). It has not yet been commonly utilized as an option for mass timber buildings, though research has shown that it is viable (Russell 2018). Before going into the intricacies of inter-story isolation systems, it is best to briefly discuss the more commonly utilized base isolation system.

Base isolation is a viable option for seismic resistance of a structure. Often made using flexible rubber bearings, a base isolation system creates a separation between underground foundation and the structure above, labeled the ‘superstructure’. The goal of the base isolation system is to cut the seismic ground motion input to the superstructure. Base isolation systems increase the fundamental period of a structure, reduce the internal forces and acceleration of the floors above, and reduce the inter-story drifts (the lateral movement between two floors). See Figure 14. The system is designed with low stiffness in order to accomplish this and allows large lateral displacements or deformations within the isolation layer. Base isolations systems are often implemented with dampers in order to mitigate the large displacement at the isolation. Specialized foundations are required to deal with significant displacement. Additionally, special connections need to be made to accommodate utilities, such as power and water, that are coming into the building. With the base isolation system, the superstructure’s lateral system is designed with a reduced lateral load demand.

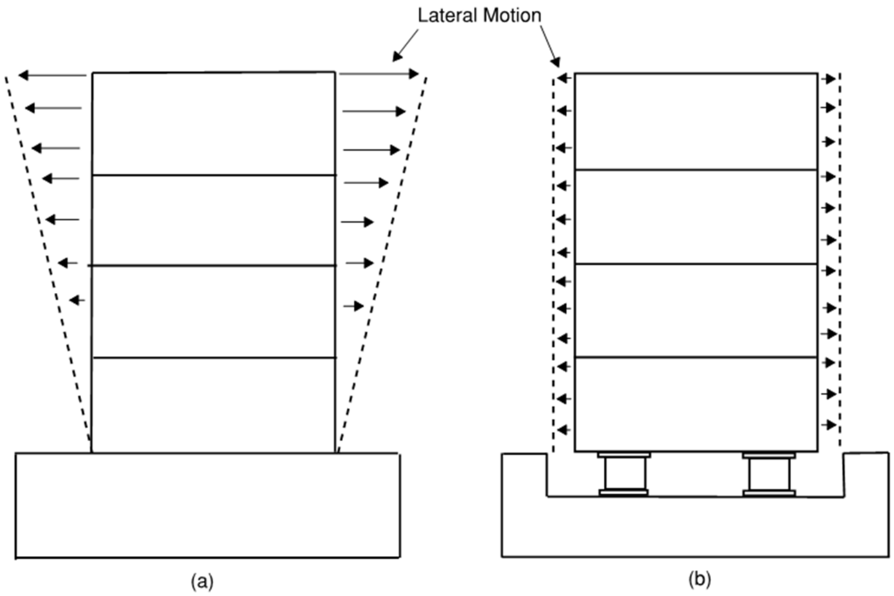

Figure 14: Lateral Movement of Structure Under Seismic Loading for a (a) Conventional Structure and a (b) Base Isolated Structure

Base isolation systems are best suited for low-to-mid-rise buildings. Issues begin to arise when dealing with high-rise buildings. In taller structures, the larger overturning moment as well as the higher loading on the isolation bearings bring with it a larger risk of damage to the isolation system. Base isolation systems may have issues with wind loading. This is because the lateral load from wind is applied directly to the building, without the filtering from the isolation layer, so the isolation system is not reducing the load effect. In low-mid-rise structures, this is not an issue, as wind load is low and usually not governing the design of lateral system in high seismic areas. However, in high-rise structures the wind loading increases significantly, and the effectiveness for a base isolation system is significantly reduced, as the lateral system of the superstructure must still be upsized to account for the wind loading (Wang et al 2012).

Inter-story isolation seeks to take the application of isolation to tall multistory buildings without the need for additional foundation work. In addition, it overcomes the shortcomings of base isolation systems regarding wind loading and risk of damage to the isolation system

(Russell 2018). Inter-story isolation allows utilization of CLT lateral systems in taller buildings for high seismic loading.

The inter-story isolation systems are installed between two diaphragms, one above the isolation system, and one below it. The location of the isolation layer can vary, and multiple isolation layers can be utilized within the structure, as is shown in Figure 15. While the isolation system can be located throughout the building as opposed to the foundation level, the system itself is not drastically different. An advantage of utilizing inter-story isolation is that the total story shear demand for the levels below the isolation layer is reduced. In addition, in cases where multiple isolation layers are utilized, each isolation system is subject to less loading than would be experienced in a base isolation system, since the loading is further dissipated. As mentioned above, one of the key issues with base isolation in tall structures is the large overturning moment and loading on isolation bearings. These issues make it difficult for base isolation systems to be utilized without large risk of damage. Inter-story isolation systems solve this issue due to their location of implementation. Since the isolation layer is further up the structure, the overturning moment and loading on the isolation bearings is drastically decreased, despite the height of the structure. This can help mitigate the number of repairs needed compared to a base isolation system, or it can help to reduce the robustness necessary for the isolation system design. One thing to note is that with inter-story isolation, the further up the structure it is implemented, the more deformation and shear is experienced by the isolation layer, which may make it difficult to implement without taking proper measures.

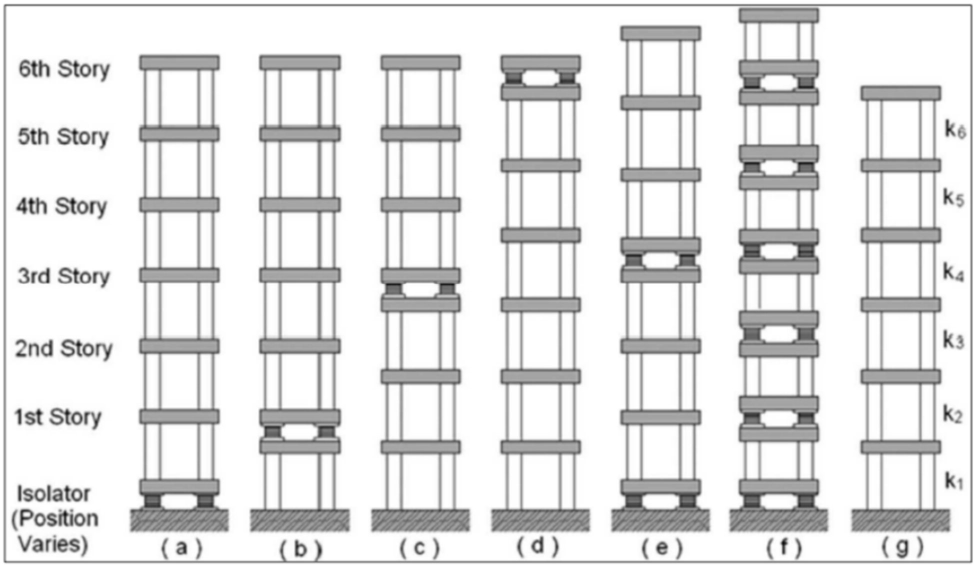

Figure 15: (a) Single Isolation System at Base; (b) at Top of the First Story; (c) at Mid-Height; (d) at Roof; I Multi-Story Isolation at Base and Mid-Height; (f) at Every Story; (g) No Isolation

Source: (Ryan et. al. 2010)

Inter-story isolation can help with the use of conventional CLT shear wall systems in taller structures. CLT shear wall systems perform well in low-mid-rise structures. However, with taller structures the accumulation of forces overcomes the strength of connections in the CLT shear wall systems. With inter-story isolation, the lower levels utilizing CLT shear walls can continue to perform adequately while the isolation layer separates the brunt of the lateral loading from the taller layers. This allows for the use of conventional CLT shear wall systems in taller buildings and under higher seismic loading.

FIRMOC System

The Floor Isolated Re-Centering Modular Construction System (FIRMOCS) is proposed by FPInnovations and is defined by using prefabricated modular mass timber units in conjunction with post tensioned rocking timber walls and integrated floor isolation. This system, unlike rocking timber walls and inter-story isolation, does not provide a new concept, but rather it takes existing innovative ideas and pulls them into a single integrated system. It takes the concepts used for both rocking timber walls and inter-story isolation and applies them to a structure utilizing prefabricated modular mass timber units. It seeks to provide an efficient lateral force resisting system for prefabricated modular mass timber construction in high seismic zones, which is typically difficult to accomplish due to the need for simpler connections between modular units. This system is made up of three key elements: prefabricated modular mass timber units, post-tensioned shear walls, and connectors between the PT walls and the modular units.

Prefabricated modular mass timber units are building unit modules that are fabricated in a controlled environment (factory) and then assembled on the construction site. These modules include portions of walls, diaphragms, and lateral systems in a single unit, with prefabricated openings as needed (Figure 16). There are many benefits to this approach, a few key advantages being less material waste, higher predictability of components, and simpler construction. These modules are connected through metal connectors, which act as the governing yielding point under lateral loading. Due to the nature of these modules, connected locations can be difficult to access, therefore connections need to be simple to install. However, this means modular mass timber construction is generally difficult to design in high seismic areas, since these simple connections are typical metal connectors (such as brackets) and have poor seismic performance. 30The FIRMOC system seeks to fix this flaw using both inter-story isolation and re-centering action, allowing for the benefits of prefabricated modular mass timber CLT construction to be obtained in taller buildings in high seismic areas.

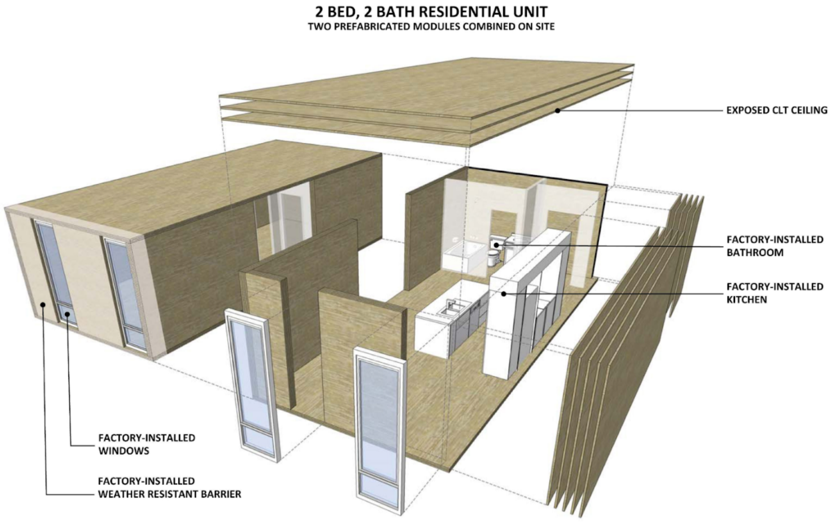

Figure 16: Pre-fabrication Modular Mass Timber Unit

Source: (Alter 2018)

This system takes the first step in solving the connection issue by taking them out altogether. This allows the modular units to be isolated from one another. The modular units are then connected to post tensioned shear walls using elastic connections. This connection can be seen schematically in Figure 17, with the elastic connections in grey, the energy dissipators in red, and dampers in blue. Just like a PT rocking timber wall, energy dissipators are utilized in this system. The post tensioned walls provide re-centering for the panels and resistance to lateral loads, using the same concept mentioned before about the decompression moment. The isolation of the modular units provides the same benefits as in an inter-story isolation system, increasing the flexibility of the system and the fundamental period of the building, which helps to reduce seismic demand. This isolation between modular units allows for them to be designed similarly to low rise buildings under a lower seismic force, which cuts down overall building cost. In addition, floor isolation reduces inter story drift, which helps to prevent non-structural damage. The energy dissipators localize yielding to themselves and prevent damage to the other components, as well as provide ductility to the overall system. The elastic connection that connects the modular units to the PT walls provides the restoring force for the modular units. This connection is bent at a 45-degree angle, because the system not only needs to deal with re-centering in the horizontal direction, but in the vertical direction as well, since the modular units are isolated from each other. A simplified 3D model of the FIRMOC system is shown in Figure 18.

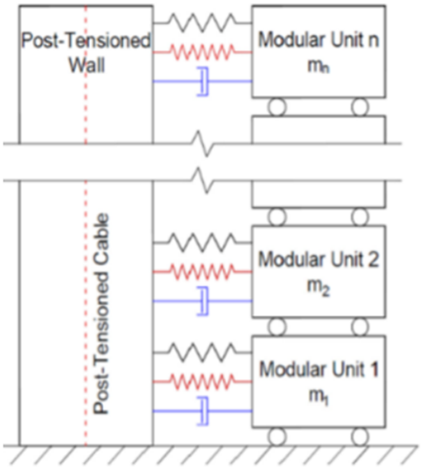

Figure 17: Schematic Model for FIRMOC SFRS

Source: (Chen et. al. 2020)

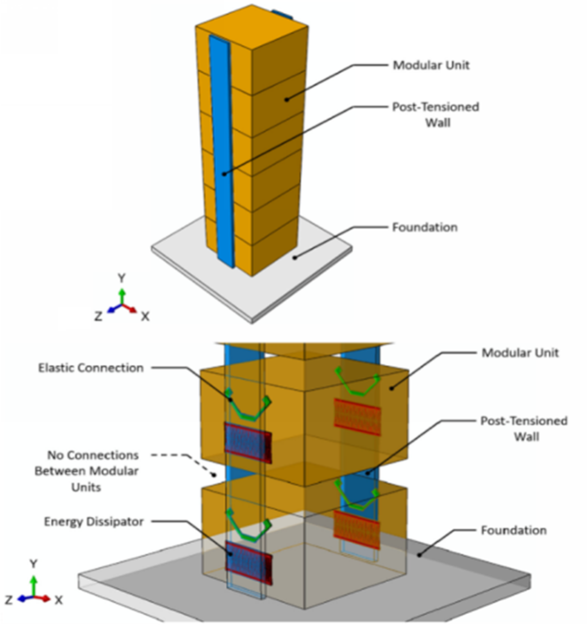

Figure 18: Simplified 3D Model of the FIRMOC SFRS

Source: (Chen et. al. 2020)

A nonlinear time-history analysis showed that the use of this FIRMOC system can reduce the seismic loading on the modular units by around 50 percent, proving the system to hold merit (Chen et al 2020). The FIRMOC System is a great example of the continual innovation of mass timber systems. It offers many benefits that come from current innovative lateral systems and merges them into a single system. Concepts are meant to be building blocks on which further discoveries can be found and innovations created. These concepts, along with the continued efforts for novel lateral systems and improvements of current innovative systems, will increase viability for taller and more seismically resilient mass timber structures.

Chapter 4: Conclusion

Mass timber, particularly CLT, is growing in both popularity and viability. With its ability to provide beautiful natural aesthetics, as well as it being a natural resource, timber is an appealing structural material for owners and architects alike. Significant research has been conducted in order to provide sufficient mass timber members for structural use. Initially used mainly for floor panels, CLT has grown to being used for the lateral force resisting system in the form of shear walls. While effective in Europe and areas of minimal seismic loading, CLT shear walls found limitations in high-rise buildings and high seismic zones, due to weakness of connections. For this purpose, innovations in CLT lateral systems have been created and researched in order to further the applicability of CLT for complete building design.

CLT shear walls fail when the overturning moment exceeds the strength of the connections. This forces uneconomically robust connections in high seismic areas. Rocking timber walls overcome this issue by allowing the wall to 'rock' after the overturning moment exceeds a certain amount. Then, as the loading subsides, a connection (either post tensioning or a slip friction joint) recenters the wall to its original position. This system drastically reduces the design strengths that are required out of the connections, allowing for CLT shear walls to be used in higher seismic areas.

The issue of overturning moment is a big issue in taller structures. Inter-story isolation systems deal with this by reducing the accumulation of the load up the height of the structure. Using inter-story isolation, CLT lateral systems that would typically fail in high rise structures are able to adequately resist the lateral loads. Contrary to rocking timber walls, inter-story isolation allows for CLT use in taller structures without the need for a new CLT lateral system.

Both rocking timber walls and inter-story isolation are viable solutions by themselves for CLT in taller structures and high seismic areas. By utilizing both innovations, further systems can be created to overcome other issues. For example, prefabricated modular mass timber units can bring many benefits to a building project, a few being less material waste, higher predictability of components, and simpler construction. However, due to the nature of their connections, they perform poorly in high seismic areas. The FIRMOC system fixes this problem by utilizing both rocking timber walls and inter-story isolation for increased ductility, increased building periods, and re-centering capabilities.

Rocking timber walls and inter-story isolation show how innovative approaches to CLT structures can provide more opportunities for timber design. The FIRMOC system shows that by finding ways to implement the benefits from multiple current systems, previous limitations can be overcome. While these systems have greatly increased the viability of CLT for complete structural design, they have not fixed all the issues that come with CLT lateral design. Further research, study, and innovation is necessary in order to make mass timber as viable as steel and concrete for building design. Future research could focus on a new connection system for rocking timber walls that also provides shear transfer. RSF joints can provide both re-centering (like PT) as well as energy dissipation, preventing the need for additional energy dissipation devices. A new connection could take it one step further, by providing shear transfer, which would remove the need for brackets as well. This would create an all-in-one connection system for rocking timber walls. Another path for research could investigate the combined use of rocking timber walls and inter-story isolation, without the use of prefabricated modular mass timber units. The FIRMOC system combined rocking timber walls and inter-story isolation, but isolation was achieved through a lack of connection between units, as opposed to an integrated mid-story isolation system. Research could be conducted into the use of inter-story isolation systems used in tandem with rocking timber walls in order to provide a more resilient structure.

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