EXPANDING OPPORTUNITIES FOR MID-RISE BUILDINGS IN CHILE THROUGH THE APPLICATION OF TIMBER PANEL SYSTEMS

by

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Abstract

During the last few years, the merging of timber building tradition with the application of new technologies has produced new prefabricated building systems in Europe and North America. Mid-rise buildings present a unique opportunity to apply new timber technologies.

Chile has shown sustained growth of buildings construction during the past decades but little further development in the use of wood. To establish the feasibility of timber systems applied to the Chilean context this research considered social aspects, technical aspects and local standards related to the manufacture and construction using timber components. A project proposal is used to analyze the architectural applications of timber systems according to the Chilean context. The design considers the case of densification in the city of Santiago and investigates the possibility of developing mid-rise structures using the structural properties and features of timber systems. So far only two systems applied to mid-rise structures have been tested for seismic resistance on full scale prototypes: Midply and Cross Laminated Timber.

Both systems are suitable for the Chilean context despite their different features. However, it is essential to modify the Chilean Structural Code in order to properly incorporate the seismic performance of timber structures. Also, further research is needed on the application of softwoods and local construction techniques are required for timber panel systems in order to change the negative perception of users about timber housing.

The Chilean context has interesting design opportunities to develop buildings that use prefabricated timber panel systems. These structures are flexible, light and have shear high-resistance. However, it is necessary further exploration on architectural possibilities that could expand the use of these alternatives.

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Glossary

Balloon Frame: Balloon frame is a timber construction method where vertical structural elements consist of studs that usually extend the full height of the frame. Floor joists are fastened to the studs.

Biomass: Biomass is a renewable energy source based on biological material from living or recently living organisms.

British Columbia Building Code (BCBC): BCBC regulates the design and construction of new buildings and modifications to existing structures in British Columbia, Canada. It is based on the model National Building Code of Canada.

Computer Numerical Control (CNC): CNC refers to the operation of machine tools through abstract programmed commands, as opposed to manual control.

Corporación Chilena de la Madera (CORMA): CORMA is the Coorporation of Chilean Timber Producers that gathers several local forestry industries to represent their interests to the public and to promote the use of timber.

Cross Laminated Timber (CLT): CLT consists of prefabricated massive wood panels made of several layers of sawn timber commonly set at 90 degrees to each other

CSA 086: CSA 086 defines structural wood design requirements according to the Canadian Standards Asociation

Embodied Energy: Embodied energy is the energy required to make a product, which includes raw material extraction and processing, energy production, transportation and product manufacture.

Engineered Wood Products (EWP): EWP consist in the combination of timber smaller components using engineering methods to develop a building product with improved structural characteristics Some examples of engineered wood products are: LVL, LSL, PSL, Glulam, OSB and I-Joists.

Eurocode 5: Eurocode 5 regulates the structural and fire design of timber buildings and civil engineering works in the European Union..

Fire Resistance Property of a building component: The Fire Resistant Property of a building component designates the minimum number of minutes for which the component remains functional when exposed to a fire (e.g. F30= 30 minutes fire resistance). Function implies both load-bearing functions and separating functions that prevent the transmission of smoke and heat.

Global Warming Potential (GWP): GWP measures the heat that a greenhouse gas traps in the atmosphere by comparing the heat trapped by similar masses of a certain gas and carbon dioxide. Carbon dioxide's GWP is standardized to 1. GWP is calculated over time intervals, usually 20, 100 or 500 years.

Glued Laminated Timber (Glulam): Glulam is a structural timber product composed of several layers of small sawn lumber bonded together with adhesives. Structural components, as well as curved elements, are used as columns or beams.

I-joist: I-Joist is an engineered wood product in which the web is sandwiched between a top and bottom flange assembled with glue. The web is typically made from timber boards and flanges can be made from solid lumber or LVL. This element has great strength in relation to its size and weight.

Instituto Nacional de Estadísticas (INE): The INE is the Chilean Census Bureau and provides indicators on censuses and surveys about employment, prices, population, buildings, economy among others.

International Organization for Standardization (ISO) ISO provides International Standards for products, services and good practice looking for global consensus.

Laminated Strand Lumber (LSL) : LSL is an engineered wood product composed from a matrix of thin chips assembled with adhesives.

Laminated Veneer Lumber (LVL): LVL is an engineered wood product composed from multiple thin laminations of wood assembled with adhesives.

Life Cycle Assessment (LCA): Life Cycle Assestment is one method in environmental management within a management system or a comprehensive ecological certification. The aim of a product-related life cycle assessment is to examine the complete life cycle of a product, from extraction of the raw materials, through its manufacture and use, right up to disposal or returning it to the cycle. The effects on the environment are determined and evaluated through a product's entire life cycle.

Massive Wood: Massive wood or solid construction refers to building components that achieve strength through lamination of various horizontal or vertical layers. In this case the load bearing capacity, shear rigidity and vapor barrier of the envelope are part of the same element.

Norma Chilena 1198 - Madera - Construcciones en Madera - Cálculo (NCh 1198): NCh 1198 is the Chilean Structural Code for Timber Structures that defines structural wood design requirements according to national standards.

Norma Chilena 433 - Diseño Sísmico de Edificios (NCh 433): NCh 433 defines seismic and structural design requirements for buildings in Chile.

Ordenanza General de Urbanismo y Construcción (OGUC) OGUC is the Building Code that regulates the design and construction of new buildings and modifications to existing structures in Chile.

Orientated Strand Board (OSB): OSB is an engineered wood product composed from layers of wood strands (flakes) in specific orientations.

Parallel Strand Lumber (PSL): PSL is an engineered wood product manufactured from long strands of veneer orientated parallel to each other glued under pressure. This product marketed under the trade name Parallam is commonly used as columns and beams.

Performance based Building Code: Code that removes the restriction to the number of storeys for which a timber building could be built if it meets certain performance criteria.

Platform Frame: Platform frame is a timber construction method in which each storey is framed independently so each floor slab lies on top of storey-high walls.

Post and Beam: Post and beam is a timber construction method in which columns hold up beams laid horizontally across their top surfaces.

Radiata Pine: Radiata is a pine species native to California that was introduced to Chile in the late 19th century. Its softwood is valued for a rapid growth and desirable lumber and pulp qualities.

Acknowledgments

It would not have been possible to write this thesis without the help and support of the people around me, to only some of whom it is possible to give particular mention here. Special thanks to my supervisor, Oliver Neumann, for his support and good advice on this work. I offer my gratitude to the faculty and staff of UBC and particularly to the Greg Johnson and Pablo Crespell for their comments and dedication as committee members.

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Dedication

To Colleen, P.J. and Totó.

1. Introduction – The Use of Wood in Mid-rise Buildings

Wood has been used in construction since the beginning of civilization, and it has proven to be an excellent material for structural applications. Through the centuries, several cases of its application in mid-rise buildings have demonstrated important attributes of the material such as flexibility, excellent thermal performance and energy efficiency.

Today, the merging of this building tradition with the application of new technologies has produced new knowledge in the use of wood. Research by public and private organizations, enhancements of existing wood products, new engineered wood products and manufacturing technologies lead to innovative timber systems. These new systems allow for improved quality standards, increased productivity levels and enable designers to use wood in mid-rise structures. Issues of strength, fire safety and durability of wood construction drive innovations for new alternatives to meet requirements and codes.

Wood plays a central role in contemporary architecture. According to Grohe (1995), the use of timber building systems provides great flexibility as an individual system or in combination with other systems (e.g. concrete or steel).

Mid-rise buildings present a unique opportunity to apply new timber technologies. During the last few years, changes in building codes and consistent application of innovative alternatives in wood building have encouraged the development of new prefabricated building systems in North America and Europe. Although steel and reinforced concrete structures are commonly used in these buildings, the use of wood is consistently increasing as an alternative to these traditional systems. "The growing interest in new timber construction technologies would seem to support the view that, for the first time in the history of architecture there would seem to be a trend away from solid to timber construction." (Deplazes, 2005, p. 77)

1.1 Tradition of a Building Material

Historically speaking construction without wood is unimaginable. Through time, timber construction has evolved in all continents with considerable variations from culture to culture. Japan has used wood as the primary building material since the Jomon period (3500 – 300 BC); pagodas of more than 50 meters height using post and beams structures can be found dating back to 16th century (Herzog, 2004). Also, Eastern Europe churches and mid-rise dwellings, dating from the 15th century, use log systems as supporting structures to achieve 5-storey buildings (Pryce, 2005). In Northern Europe the use of log structures was common until the early 20th century when it was displaced by the frame system mainly due to cost considerations (Falk, 2005). North America has a 200-year tradition in wooden construction, and it is common to find 4-storey buildings structured in “platform-frame” system. Mid-rise timber buildings have been common architectural expression consistently across different cultures.

The use of timber structures remained constant until the 19th century when the densification of cities, exploitation of forests and devastating fires led to the need to regulate building and house construction through codes. According to Pryce (2005) the emergence of new building materials as part of the industrial revolution was considered as part of the "spirit of the age". The desire of architects to reflect a non-regional expression led them away from the use of wood. In most of Europe, timber was not allowed for load-bearing structures of more than two storeys due to fire regulations until 1994 (Falk, 2005). In New Zealand, prior to 1992, timber construction was limited to 3 storeys, and the timber industry was mainly focused on single-family house construction. Therefore, multi-storey residential buildings were developed in techniques based on the use of other materials (Banks, 1999).

Wood is considered a combustible building material. However well designed timber buildings satisfy fire requirements through the correct combination of building component layers and building materials; a method known as encapsulation. For example load bearing walls are covered with plasterboards and filled with an insulating material. Exposed timber components with load-bearing functions comply with the fire protection requirements because charring occurs in larger cross-sections to form a layer of charcoal which acts as natural insulation. This layer prevents a temperature rise in the remaining wood. This insulation against fire damage is one of the great advantages of wood structures compared to steel (Wagner & Zeitter, 2004).

In the early 1990's, performance-based building codes, and increased fire protection regulations allowed higher timber structures in Europe and New Zealand. Due to the significant increase in both the number and size of multi-storey timber buildings, researchers looked for new timber system alternatives. These alternatives needed to achieve greater strength and competitive production costs against other materials such as steel or concrete. A competitive system could be achieved through the prefabrication of components.

In the mid 1990's, massive wood mid-rise housing appeared in Switzerland, Germany and Austria; later in Sweden, Norway and Denmark. The building systems used in these projects were developed by engineers and architects and also through academic research. Still today, these systems and their techniques are in a constant process of refinement.

From 2000 on, timber construction has achieved remarkable growth due to the green building movement and due to better efficiency in the European market. Currently, the European wood industry produces 300,000 cubic meters of massive panels per year, with Austria as the main manufacturer with 63% of the production. Considering the exponential growth in wood production, 1 million cubic meters can be expected by 2015 (Schickhofer, 2011).

Prefabricated massive timber panels (CLT) are a well established building system in Central Europe, and it is common to find 7-storey wood buildings that support the feasibility of this system. For example the Murray Grove building by Waugh Thistlenton Architects in London (2008) reaches 9-storeys (Figure 1).

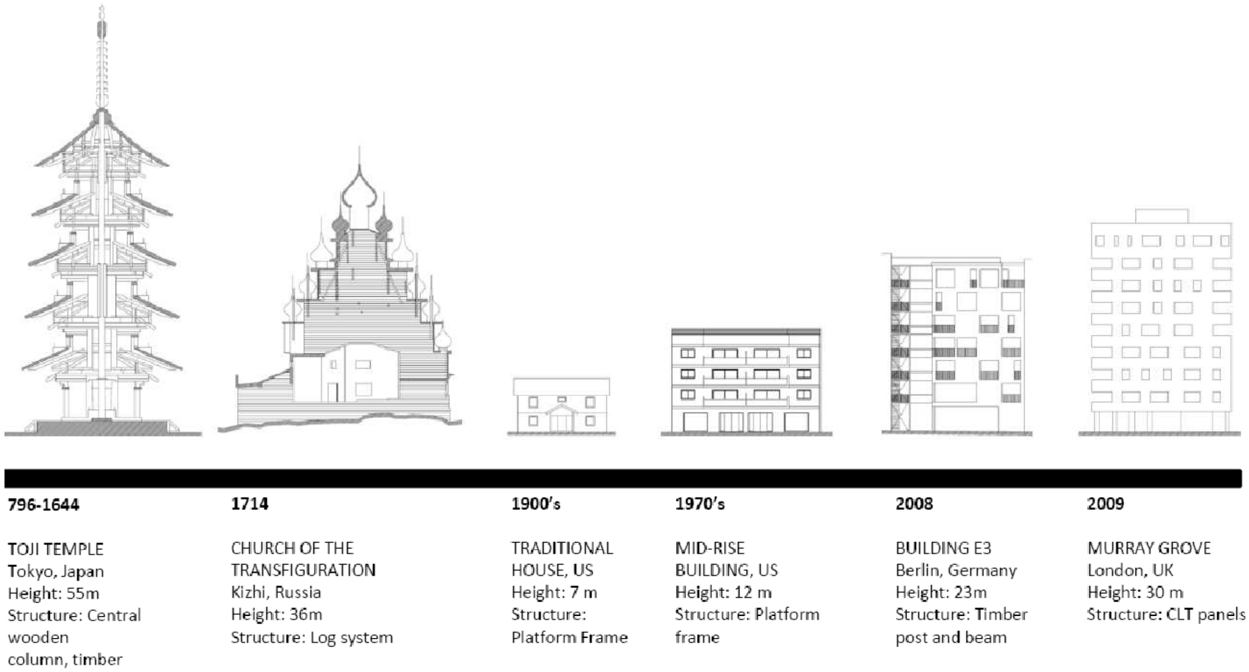

Figure 1: Traditional and recent mid-rise timber buildings. Source: (Herzog, 2004)

Currently ONE LCT, an 8-storey timber building, is under construction in Dornbirn, Austria as part of the "Life Cycle Tower" project developed by the Rhomberg Group. Its design considers a post and beam structure of timber laminated (glulam) elements combined with wood and concrete slabs. The application of this combined building system has been evaluated for 30-storey buildings.

1.2 Current Applications

Wood is a naturally grown organic material. Trees have evolved in complex structures to carry their own weight and other loads such as wind. Wood is composed of cells and vessels which provide the tree with water and nutrients. The structure, distribution and orientation of cells are the determining factors for the density and strength of wood. The longitudinal configuration of the cells defines the anisotropic structure. Parallel to the grain, wood can carry tensile and compressive stresses with ease but perpendicular to the grain, it has a lower compressive strength (Deplazes, 2005).

These properties make it different from other building materials that are more homogeneous, stable and industrially produced. However, lately the development of engineered wood products has reversed this trend through the incorporation of new wood based products that combine the properties of wood particles with other components. The log is the basic element of wood products. All other wood products are manufactured from this element. Sawn timber is the most direct derivate product that converts the log in rectangular sections preserving all the anisotropic properties of the tree trunk. However, by sawing the lumber in smaller pieces and gluing them back together anisotropy can be overcome to produce homogeneous products.

Today, there is a wide range of engineered wood products that optimize the resources of raw material. These semi-finished products use the "waste" of manufacturing processes by combining wood particles of various sizes with synthetic resin adhesives or mineral binders. These processes can produce large standard components that homogenize the irregular properties of wood to reduce the anistropy and unpredictability of the material (Deplazes, 2005).

The manufacture of Glued Laminated Timber (Glulam), Cross Laminated Timber panels (CLT), ply boards and Parallel Strand Lumber (PSL) can produce elements with standard structural properties and dimensions. Thus a classification of wood products can be established according to their level of isotropy i.e. their level of uniform structural behavior in all directions (Table 1).

According to Falk (2005) these products can be classified into three main groups: structural composites, structural plates and glued beam products. The first group consists of Parallam, LVL and fiber-composites of wooden fibers mixed with plastic. The second group considers OSB, plywood, laminated plates and cross-laminated timber panels. The third group considers Glulam, I-beams and sawn timber.

Table 1: Classification of wood products according to the dimension and orientation of their components. Source: (Augustin, 2008)

		Grain Orientation of the Components		
		Orientation of components in one direction	Orientation of Components in orthogonal direction	"Random" Orientation of Components
Basic Wood Component	Wood fibres (Particles)	Extruded Products	-	Fibreboards; Particle (chip) boards
	Strands	Longitunal Strand Lumber (LSL); Parrallel Strand Lumber (PSL)	Orientated Strand Lumber (OSB)	-
	Veneers	Longitudinal Veneer Lumber (LVL)	Plywood; LVL with Orientation of some Veneer in Tranverse Direction	-
	Boards	Gluelam	Cross Laminated Timber (CLT)	-

Traditionally, timber techniques have been successfully applied to mid-rise buildings but fire-safety regulations have limited the height of these structures. Recent modifications in codes and new building techniques have allowed multi-storey timber buildings. Today, platform-frame is a feasible building system for 6-storey structures. However, new developments on timber systems are expanding their possibilities into higher structures. Massive timber systems are feasible for 12-storey structures and recent proposals on heavy timber frame systems applied to high-rise buildings are a new alternative in a field exclusively reserved for steel and concrete structures (Figure 2).

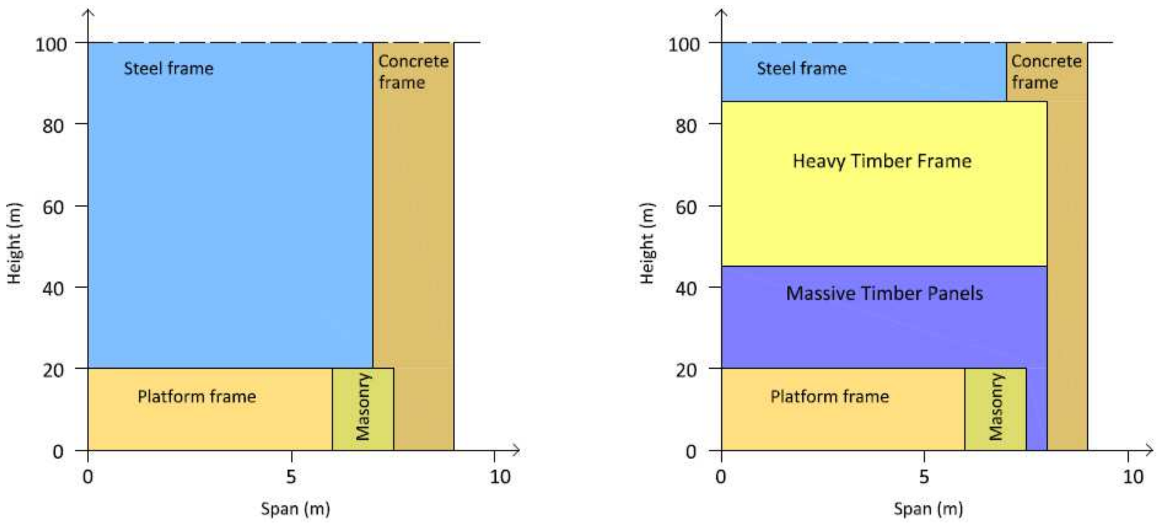

Figure 2: Left: Span and height capabilities of traditional structural systems in multi-storey buildings. Right: Span and capabilities of structural materials according new developments in timber systems. Source: (TRADA, 2009)

1.3 Sustainability Features

Construction of buildings is an energy intensive activity. The World Business Council for Sustainable Development reports that buildings consume 32% of all resources, 40% of all energy and are responsible for 40% of global landfill waste (Copland, 2010). Deforestation is a critical contributor to climate change, and 12 to 15 million ha of forest are lost every year in the southern hemisphere of the globe (Herzog, 2004). Wood products are commonly seen as unsustainable materials due to the high deforestation evidenced years ago related to the forestry industry. Unfortunately, this argument is used to discredit wood products when “in reality, of all the mainstream structural materials, wood is the only renewable resource” (de la Roche, Dangerfield, & Karacabeyli, 2003, p. 11).

Today, forests account for about 3.9 billion ha worldwide and 43% of these forests are located in the industrialized world (Herzog, 2004). Growing forests remove CO_2 from the atmosphere and store carbon in trees and soil. Some carbon is released back to the atmosphere through forest fires, wood manufacturing processes, etc. However, the success of carbon sequestration relies on sustainable forest management and forest certification which increase sustainability of wood as a building material (Figure 3).

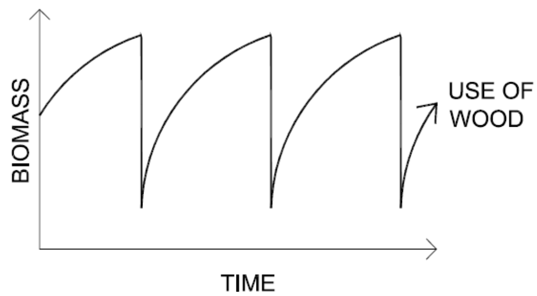

Figure 3: Biomass development in a managed forest whose carbon store is emptied again and again by using the wood, so that the forest can then extract additional CO2 from the atmosphere. Source: (Herzog, 2004)

Sustainable forest management models are highly important for the viable use of land and resource policy. “In the tense relationship between sustainability and ecological, economic and social aspects, the importance of wood has rarely been considered up to now, and has been undervalued in climate policy discussions” (Wegener & Zimmer, 2004, p. 47). Today Western European forests -after witnessing a 70% deforestation during the middle ages- are marked by a sustained growth of 30% since 1990 (Pryce, 2005).

The process for preparing wood and constructing wood buildings is energy efficient. The “embodied energy” in the production of building materials such as steel (32 MJ/Kg.) or aluminum (227 MJ/Kg.) are much higher than in the case of wood (2.5 MJ/Kg.) (Canadianarchitect.com, 2011). The use of wood in construction also means a significant reduction in CO_2 emissions compared to other building systems when the life cycle of the building is considered as a long-term impact indicator. The carbon absorbed as the trees grow exceeds the carbon associated with the materials during the construction process (Figure 4). "When the eventual decay of the wood is taken into account, a wood structure will usually have a lower net emission than others"(TRADA, 2009, p. 7).

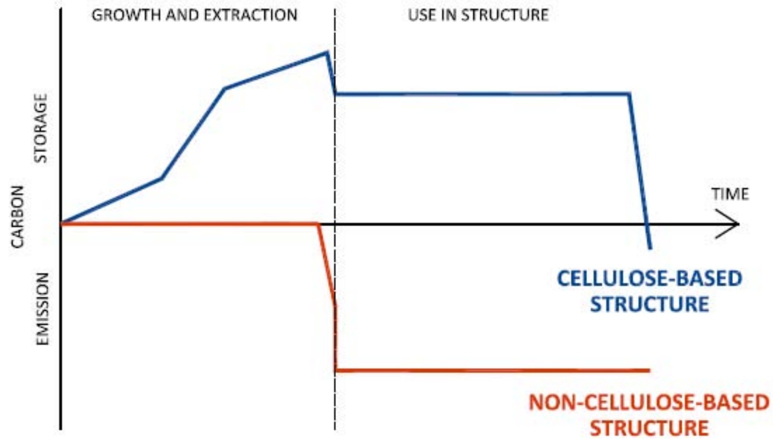

Figure 4: Impact of cellulose materials on carbon storage and emission. Source: (TRADA, 2009)

An environmental analysis on concrete structures vs. timber massive systems in mid-rise buildings reported 14 to 71% advantage in wood systems. Wooden buildings obtain 60% of energy from renewable sources compared with 20% in concrete buildings (Robertson, 2011). A comprehensive report from the University of Canterbury (John et al., 2009) analyzed the environmental impacts of multi-storey buildings using concrete, steel and timber structures. The research considered the influence of construction materials on the initial and operational energy consumption and global warming potential (GWP) of the different cases. Although steel building has a significant GWP reduction when structural steel is recycled, the timber building shows the largest energy recovery and GWP reduction (Figure 5).

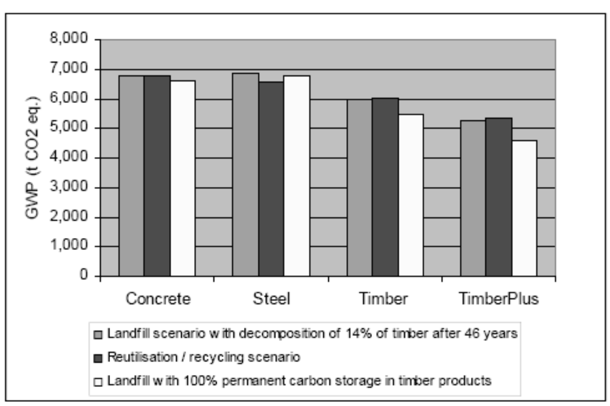

Figure 5: Net lifecycle Global Warming Potential (GWP) emissions for the four buildings showing comparison of different end-of-life scenarios. Source: (John et al., 2009). Used by permission.

2 Research Scope

So far, universities have been the primary researchers of architectural and structural possibilities from a theoretical perspective that do not consider local conditions or restrictions. However, specific researches are used as reference for performance-based building codes. New codes and standards encourage manufacturers to develop new constructive systems that meet those requirements. These products apply practical knowledge to a global market. In the building process is where products' performance is applied to the local context and practical construction considerations(Figure 6).

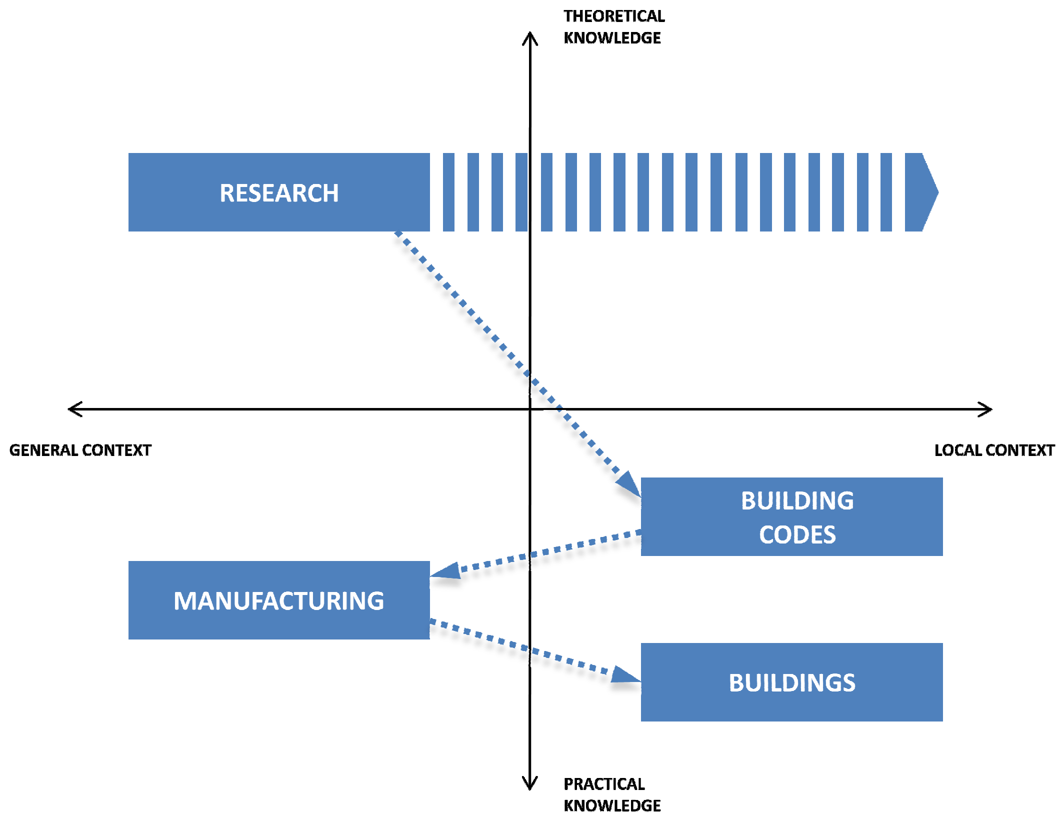

Figure 6: Scope of this research. Theoretical knowledge applied to the local context can set guidelines for local building codes, new manufacturing processes and building projects.

This research investigates timber systems applied to a specific context in order to analyze their implications regarding local codes that could encourage new manufacturing processes and, in the end, the design of buildings.

This thesis considers the case of Chile as a country with abundant natural resources and a tradition in timber construction that has not been able to consolidate wood as a building material for mid-rise buildings. Also Chile is a country located in an active seismic area and the respective design requirements represent a challenge for the performance of these new technologies.

Thus, Chilean codes are used as reference in the architectural proposal to assess the feasibility of the design. However, timber systems are not specifically considered within a Chilean building code that focuses on concrete construction. The existing code in Chile, however, is used as the best way to approach a real design scenario. Changes in the building code are necessary in the short term to incorporate these systems in the Chilean context.

2.1 Use of Timber in Mid-rise Buildings in Chile

2.1.1 Market Share

Today, 86% of Chile's population lives in cities (INE, 2012). During the last decade the number of new buildings has increased steadily varying between 90.000 and 150.000 new homes per year. (Comisión Asesora de Estudios Habitacionales y Urbanos, 2012)

Santiago de Chile is the capital and largest city in the country and density sprawl to accommodate population growth has been traditionally argued. However, with the implementation of new regulatory plans this trend is reversing according recent market reports. Downtown areas grew 9% between 1992 and 2002 compared to 38% growth between 2002 and 2011 (Labbe O., 2011).

Market reports reflect a trend towards the purchase of apartment units instead of houses. Today, housing development in Santiago de Chile is moving towards infill and additions while the city continues to expand to a lesser extent (Poduje, 2011).

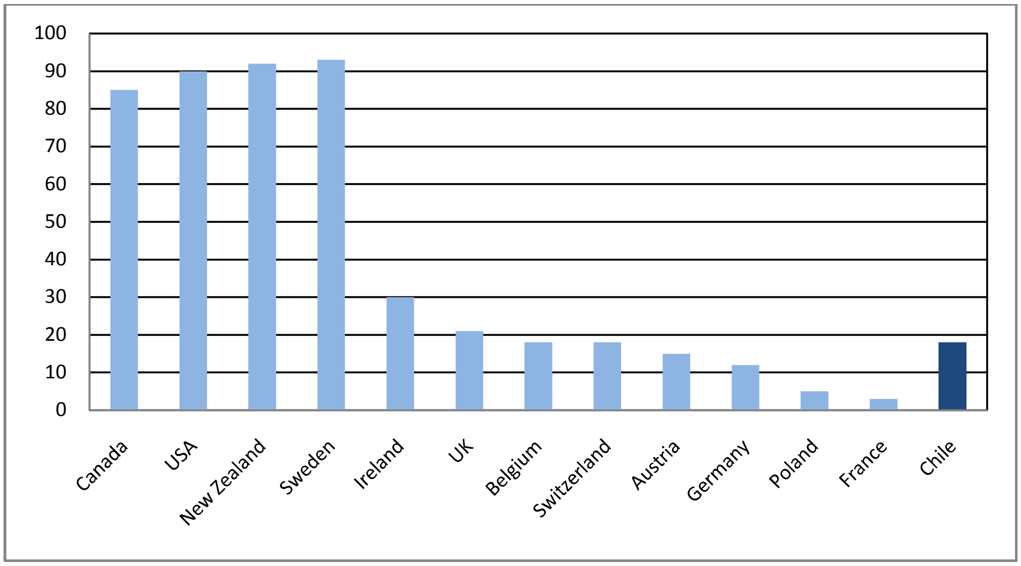

Figure 7: Market Share of House Construction in Timber. Source: (Wahl, 2008)

Despite the constant growth of housing production in Chile during the last decades, only 18% of Chile's housing is made of wood (Instituto Nacional de Estadisticas, 2011); and in most cases wood is used for one or two storey houses. This figure is very low compared to USA and Canada, both of which exceed 80% of wood based buildings. However, other countries like UK, Austria, Switzerland and Germany show a share of house construction in timber similar to the Chilean market. In all these countries timber systems have been successfully used in mid-rise structures and set a precedent for their application in the Chilean context (Figure 7).

Traditionally, multi-storey buildings have been developed using techniques based in reinforced concrete and reinforced masonry (Figure 8). The massive use of softwoods has led timber construction to be considered by the users as a low-standard building material.

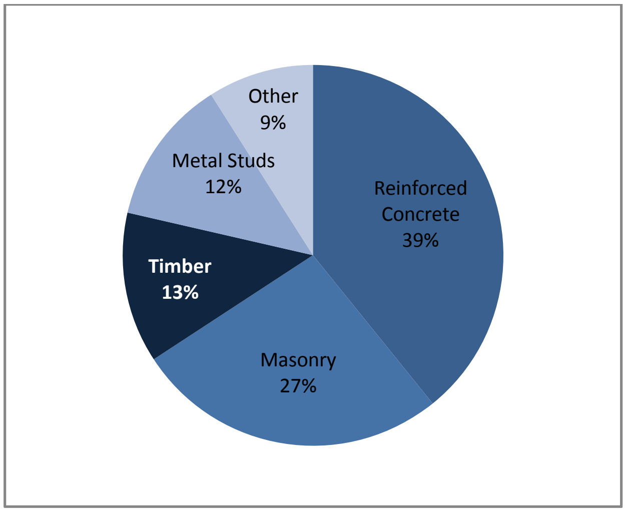

Figure 8: Construction materials used in walls in Chile, 2010. Source: (Instituto Nacional de Estadisticas, 2011)

Moreover, the local construction code in Chile has not included or studied the new timber construction systems to certify their structural performance, insulation, and fire resistance performance. Construction in timber is underrated. Low quality of timber, lack of appropriate technologies, and lack of a building tradition with wood are usually argued as the main reasons to explain this phenomenon. However, Chile as a country in an active seismic zone must explore the alternatives of new building systems to enhance housing solutions.

2.1.2 Developers

Developers identify brick masonry and reinforced concrete as their favorite building materials for houses and buildings. According to them, the massive use of wood is restraint due to a higher demand of other systems in the market and fear post-sale issues. Today, developers mainly use timber in upper storeys of houses, second housing and social housing. Elements such as prefabricated trusses, partitions, interior finishes and exterior sheeting are also regularly built in wood. Developers are aware that Chile has vast timber resources and also about the advantages of its thermal, acoustic and seismic performance.

Developers who support the use of wood reached 20%; they suggested that a "change of mentality" of Chilean users was needed as people usually favor other building materials. Despite developers argued lack of information on new technologies and the availability of certified timber systems, 65% stated a conditional acceptance to experience new timber alternatives (Figure 9).

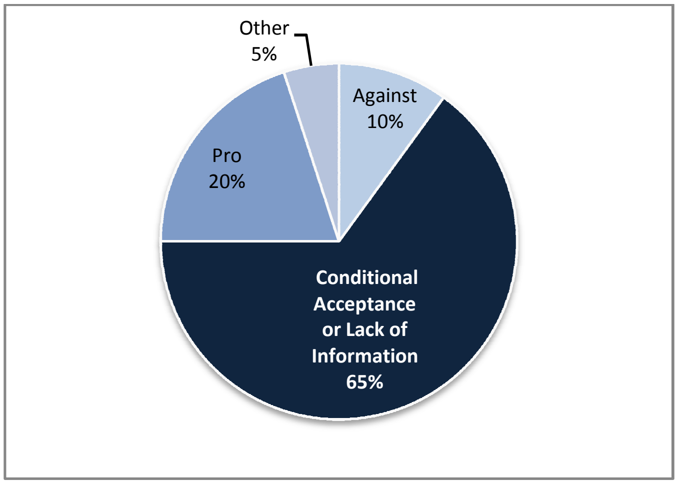

Figure 9: Developers willing to use timber systems. Source: (Collect, 2008)

2.2 Traditional Timber Architecture in Chile

In Chile, as a former Spanish colony, vernacular houses preserve a strong influence from Spanish culture. Adobe houses have been built extensively; they are particularly common in the country. Traditionally in Chile, multi-storey buildings have been developed using techniques based in reinforced concrete and reinforced masonry (Figure 10). However, a strong timber tradition in architecture is also present in Chile. In general, traditional timber precedents were built using hardwoods; the designs were strongly influenced by building techniques imported from the northern hemisphere. All timber structures were subsequently adapted to the labor capabilities and technological possibilities in Chile, and the final result is a mix of imported and local building techniques.

Figure 10: Left: traditional Chilean adobe house, Santiago © (Rivera, 2010). Right: Multi-story residential buildings constructed using concrete in Chile © (WTF Formwork, 2011).

Jesuit missions from the 18th century had a significant impact on the ecclesiastical architecture of Chiloe, an isolated region located in the south of the country. The Jesuit tradition encouraged the participation of indigenous communities in the religious life. The churches were built by locals using unprecedented techniques that mix local and foreign traditions to produce a unique form of wooden architecture (Figure 11). Structures were built using local timber species such as larch and cypress; lumber was connected by dowels instead of nails. Towers up to 20 meters-high were built with hexagonal or octagonal drums to reduce wind resistance and solid wooden columns support the aisles of the horizontally volume. Different styles can be recognized according to their influence in the design such as Gothic, Classic or Baroque Architecture. By the end of the 19th century, over 100 churches had been built; between 50 and 60 survive to the present day, and 14 of these as designated as World Heritage (UNESCO, 2012).

Figure 11: Church in "Santa María de Loreto", Achao, Chiloé, Chile © (Basaure, 2007)

Port cities are relevant in the development of timber architecture in Chile. These cities experienced a significant expansion in the last decades of the 18th century. Professionals, skilled workers and foreign settlers move out from harbor areas and downtowns to occupy surrounding areas. In the cities of Valparaíso, Talcahuano, Puerto Montt, Iquique and Antofagasta middle-class and low-class housing was built using wooden-vessels construction traditions combined with foreign techniques. Timber houses were built with interior finishes in wood while the outside cladding was built using zinc, wood or shingles. These models represented a break with the Hispanic tradition in cities like Iquique and Antofagasta, while architecture in Valparaiso is a combination of styles brought by British immigrants and the Spanish colonial style. After the reconstruction of the city after the earthquake of 1906, it was decided to use seismic constructions systems, such as wood (balloon frame), cast iron and steel. Later, many of these buildings would be replaced by masonry structures but timber structures still can be found in large numbers in cities such as Iquique and Puerto Montt (Benavides et al., 1994). Iquique was the main nitrate mining town in the north of Chile during the 19th century. Due to the economic wealth generated by the industry, important houses were built with Oregon pine imported from USA and Canada. These houses are based on balloon frame structures according to North American standards. Buildings adapted to the desert climate incorporated local architectural elements such as flat roofs and verandahs (Figure 12).

Figure 12: Palacio Astoreca, Iquique, Chile, 1903 © (Mircalla22, 2010).

Probably the most emblematic case of timber architecture in a mining town is the camp of Sewell of the Braden Copper Company. It is located in the central region of the country. From the beginning of the 20th century until the ´60s, it had a population of 15.000.

The Platform-Frame system was used to erect 4-storey housing buildings that adhered to overseas standards (Figure 13). Wall frames were built using 2"x6" studs in the lower storeys and 2"x4" studs in the upper storeys keeping a maximum distance of 2'-0" on centre. Floor-joists (usually 2"x10") distance was 1'-6" on centre. Therefore, 4 floor joists and 3 studs were distributed every 6'-0". In the first buildings, foreign timber was imported and manufactured ready for assembly on site. Then Chilean hardwoods were found suitable for the project and imported lumber was replaced by oak, "coigue" or "araucania" pine.

Two adaptations to the plans from USA were made according to the local context. The introduction of diagonals into walls due to high wind (140 km/h) and seismic loads and the addition of a 75 mm concrete slab to the floor structure as a fire resistant element (Gómez L., Leser S., & Salomone R., 2003).

Figure 13: Platform frame residential building N118 in Sewell. (1907-1978). © (Gaborel, 2010)

In southern regions of the country, the influence of European timber techniques can still be found. In 1845, German immigrants settled in that area as part of a government program to unify the country and populate uninhabited areas of the country that were dominated by indigenous communities. Between 1850 and 1875 about 7000 settlers moved into the Lake Llanquihue area and the cities of Valdivia and Osorno. German immigrants built wooden houses using their own techniques that included the use of massive wood and other traditional German styles such as Hallenhäuser or Hallenhaus typologies. Some elements from German architecture are still recognizable. It is also possible to German identify carpentry techniques applied to construction systems (Prado et al, n.d.). By the late 19th century 10,000 immigrants had settled in the south of Chile. Frenchs, British, Swiss and Spanish settlers joined the German immigrants generating architecture of great diversity and heterogeneity. Swiss architectural styles still can be noticed in the city of Victoria, while the town of Capitan Pastene features examples of Italian timber architecture (Cerda Brintrup, 2009).

The environmental performance and flexibility of wood as a building material gained acceptance and was used for housing construction in rainy areas of the country. However, design of houses was redefined by the introduction of new architecture styles. In the 20th century the traditional style was influenced by modernism (Figure 14). A simple volumetric layout and elements such as ribbon windows and curved walls were incorporated in timber houses (Cerda Brintrup et al., 2005).

Figure 14: In the early 20th century, timber housing in the south of Chile was influenced by modernism. Left: House in Puerto Montt. Right: House in Chiloe. Source: (Cerda Brintrup et al., 2005). Used by permission.

During the last century, especially since the 1960s, attempts were made to use engineered wood products (specifically Glulam) as an alternative for traditional building systems. However, it was not until the 90's that they experienced a considerable growth in their implementation. The improvement of manufacturing processes and the implementation of emblematic projects such as the Chilean Pavilion in Seville Expo 92 by Germán del Sol and José Cruz expanded timber possibilities (Figure 15). So far Glulam beams have been mostly used in long-span structures like industry warehouses or bridges because of its versatility and material quality. More recently, they have also been used in office buildings. However, they have not reached the same level of implementation as in the northern hemisphere.

Figure 15: Chilean Pavillion - Seville Expo '92 (German del Sol and José Cruz architects, Spain, 1992). Source: (Del Sol, n.d.) Used by permission.

According to these cases, it is safe to assume that Chile does have a considerable tradition in timber construction. In general, as stated, vernacular timber architecture in Chile was strongly influenced by building techniques from the northern hemisphere. These building techniques were adapted to the labor capabilities and technological possibilities of the country and resulted in a mix of imported and local building techniques to form an eclectic architectural style.

Most traditional timber architecture was built using hardwoods. However, today softwoods constitute the national forestry main product. Initiatives to develop the use of wood have had to adapt to the available wood resources and had to look for opportunities to implement timber of lower grade. The main initiatives are led by the Corporation of Timber Producers (CORMA) and educational institutions. CORMA is the main promoter of wood as a building material through research to improve and encourage the use of national forest resources. The Center of Innovation and Development of Wood (CIDM) at the Catholic University of Chile has researched the use of new timber systems in social housing and is currently studying possibilities of timber in mid-rise buildings. Related studies are in process at the engineering department of the University of Concepción who has applied for funds to investigate the seismic behavior of timber shearwalls in mid-rise buildings (Giuliano Morbelli).

Private initiatives developed in the south of the country have studied the possibilities of prefabricated massive timber systems. JMS Engineering Design Consultants have developed a Dowelled Massive Timber System (MST) made from radiata pine studs and eucalyptus dowels. So far the system has been successfully used in two-storey houses (Figure 16).

Figure 16: Dowelled Massive Timber System (MST). Source: (JMS Engineering Design Consultants, n.d.) Used by permission.

After the 2010 earthquake in Chile, new timber building techniques appeared as an feasible alternative for seismic resistant structures. Articles and specialized journals foregrounded the positive features of the application of wood building methods to mid-rise structures (Chapple, 2011). However, after some time the impact of the disaster in the media diminished and the focus on timber structures weakened.

3. Research Questions

Today, in Europe and North America timber structures are common due to long building traditions, appropriate management of natural resources and constant development of new manufacturing processes. Wood as building material is experiencing a new revival due to the combination of research initiatives, applications of new technologies and industries with high-standard manufacturing.

Meanwhile, Chile has shown sustained growth of buildings construction during the past decades but little further development in the use of wood. Is it feasible to apply new timber systems to the Chilean mid-rise housing industry?

Traditional techniques in timber construction have been strongly shaped according to different cultural contexts. In the same way, new technologies must also adapt to new contexts and local possibilities. A building systems needs to be coordinated with local techniques and the local cultural context in order to be applied successfully. Chile's manufacturing processes still show a strong reliance on traditional methods. New technologies urgently need to adapt to these conditions to become a feasible product.

Progression in the construction industry requires new technologies but also new knowledge to be incorporated. What are the architectural applications for new timber systems according to the Chilean context and local standards?

Chile is still struggling to develop mass produced housing as an alternative to traditional building systems to support population growth. Today, there is renewed interest in the use of timber in architecture in Chile because of the potential of wood as a renewable material. Furthermore, after the 2010 earthquake, wood construction presented itself as an alternative to traditional systems even for mid-rise buildings due to its seismic performance.

The goal of this research is to determine the feasibility of timber systems to mid-rise buildings in Chile according to local building codes and technical requirements. The objective is to evaluate the limitations for a project of these characteristics and to determine if changes in the code or technical improvements are necessary to meet requirements. This study explores possible architectural applications for timber system according to the local context through a design proposal that is responsive to cultural and also technical requirements.

3.1 Assumptions and Limitations

Currently, the development of innovative timber systems is not limited to panels. For example, New Zealand manufacturers have recently developed post-stressed post-and-beam timber structures (Buchanan et al., 2009). These systems can have an important impact on future industry.

This thesis does not study the specific case of 3D prefabrication because it represents a case study in itself. However, prefabricated volumetric elements can be complemented by the addition of plane component for staircases, balconies or mezzanines floors.

However, this thesis focuses on panel systems as they represent a better fit to the structural schemes of the case study. Building tradition and structural codes in Chile have led to wall-based structures in buildings because of their superior performance under seismic loads.

During the last years, public and private organizations of developed countries have studied new timber panel systems in order to validate them as a feasible building method from a technical perspective. Currently in Canada, institutions such as WoodWorks! and FPInnovations are working on general constructive and structural analysis to develop an ISO standard to meet North American standards. The new standard aims to be accepted into Building Codes by 2015 (FPInnovations, 2011). However, this study has not yet considered standards from other regions.

The proposed timber systems have no ISO certification to ensure their fire, thermal or acoustic performance. The case study uses specific calculations or is based on European standards; the proposed design is not an accepted standard solution that can be used as reference for other projects. Therefore, although is in constant development, prefabricated wood panels are a well established product in the market with sustainable manufacturing processes, and that wood is a renewable building material that can be obtained from sustainable managed forest. For purposes of this thesis two systems were chosen by considering the available information and level of development as architectural design products. New studies on systems arise every year and also local conditions change constantly, so the proposed systems are not the only alternatives that can be applied in the Chilean context.

The expansion of mid-rise housing buildings is used as a particular case study. Additions are used where timber elements are suitably combined with main structures of other materials like masonry or concrete. Generally these cases have relatively low structural demands on new joints or reinforced foundations (Falk, 2005). This scope is also applicable to other typologies that require significant expansions such as office buildings, educational buildings, etc.

Although the social context is considered as a variable of the research, the study assumes an acceptance and market interest in these systems. Budget concerns are not considered as restrictions to developing the project.

3.2 Methodology

To establish the feasibility of timber systems applied to the Chilean context this research considered social aspects, technical aspects and local standards related to the manufacture and construction using timber components. Availability and quality of timber products will impact the market feasibility, while codes and standards regulate the manufacturing feasibility of building components. This study considers the different characteristics of new timber building systems that affect the architectural design. Only by considering their unique properties and features, the design can achieve the spatial configuration and material expression of the system itself.

A project proposal is used to analyze the architectural applications of timber systems according to the Chilean context. The design considers the case of densification in the city of Santiago and investigates the possibility of developing mid-rise structures using the structural properties and features of timber systems.

Chapter 1 gives an overview on timber systems applied to mid-rise structures in the history of architecture, current applications and features of wood as a sustainable material.

Chapter 2 defines the scope of the research and introduces Chile as the case study.

Chapter 3 outlines the work through thesis questions and objectives. The chapter describes the thesis methodology, assumptions and limitations.

Chapter 4 analyses the feasibility of timber systems applied to the Chilean context. Social, cultural, technological considerations and building codes are presented as the parameters to determine if the proposed timber systems are applicable to the case. General features, prefabrication and construction possibilities of timber panel systems are presented and applied to the case study. Advantages and disadvantages of their architectural configuration, manufacture, structural and environmental performance are parameters to be considered. Conclusions discuss the benefits of the systems in order to determine the most feasible application in the case study context.

Chapter 5 introduces the state of the art of existing timber construction systems. Then an architectural design is proposed as an application of the system to the Chilean context. This proposal considers the scenario of densification of cities in Chile as an opportunity to use prefabricated timber systems. The design considers a flexible and generic solution as a proposed architectural configuration. Also specific building details and code considerations are applied to the local context that could be used as reference in other projects.

Chapter 6 presents the conclusions, scope of the study and description of possible follow-up research.

4 Feasibility Analysis

To evaluate the feasibility of timber systems applied to the Chilean context this research considered the following aspects:

- Resources Availability: Analysis of the forestry industry and timber main products.
- Manufacturing Feasibility: Features and costs of prefabricated building elements in Chile.
- Market Feasibility: Perception of wood as a building material by Chilean users.
- Structural performance: General references for maximum spanning length, cross section dimensioning, etc. Seismic structural behavior of floor, roof, wall panels and connectors.
- Local Building Codes and Standards: Environmental and fire performance: The environmental performance of the building is mainly defined by its enclosure. Insulation and fire-safety requirements have direct implications in the design of exterior wall and roof assemblies.

4.1 Resource Availability

4.1.1 The Forestry Industry

Chile is a country with vast timber resources. The forestry sector is the second largest economic activity in the country, and it has shown a sustainable growth since the ´70s (Figure 17). Today in Chile there are approximately 15.4 million hectares of forest that represent 21% of the area of the country (Fritz, 2004). Historically, a wide variety of species have been introduced in the Chilean forest. Fast-growing softwood species like Radiata Pine and Eucalyptus were imported from the U.S.A. and Australia, and now they represent the base of the forest industry. Currently, Chile produces 21.5 million cubic meters of roundwood and 77% of the total production is Radiata Pine. This softwood specie occupies 9% of the total forest area; there are almost 20 million m^3 of sawn wood available (Fritz, 2004). Chilean timber production estimates doubling its availability in the next 25 years; the main resource will probably be Radiata Pine.

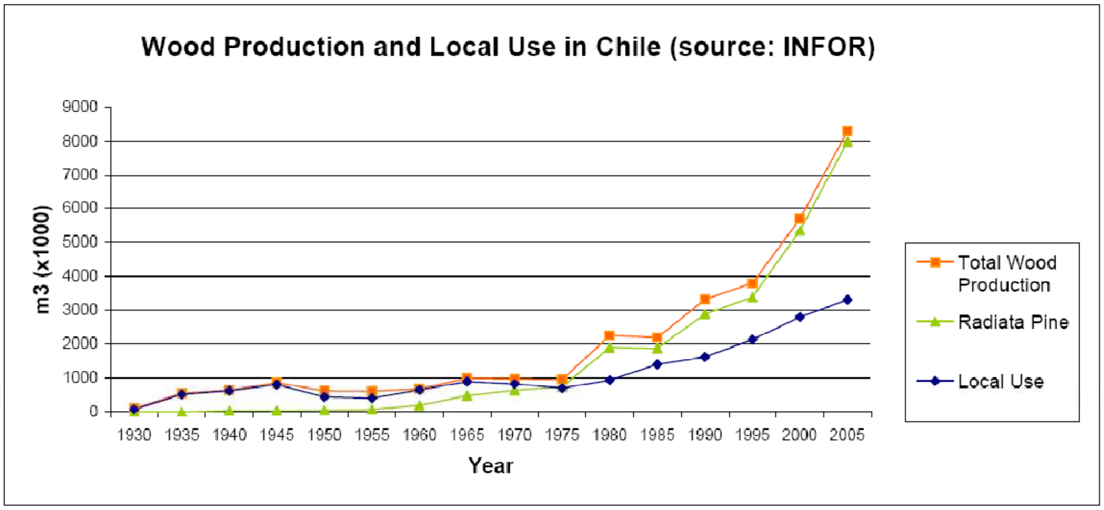

Figure 17: Wood Production in Chile (1930-2005).

Usually, sustainability and deforestation of fast-growing species forestry are questioned. A research by Eco Nativa (Cerda et al., 2002) concluded that Chilean forestry is absolutely sustainable. Commercial stocks of timber showed a sustained growth and CO_2 capture showed a positive balance. However, biodiversity may be affected by extensive plantations. The research notes that the discussion of sustainability in forestry should be reoriented.

Wood quality standards are defined by the Chilean Code NCh 1198-2006 "Wood - Timber Buildings - Calculations" that specifies visual and mechanical classification methods. Visual classification is the most widely used method due to economic reasons and convenience of the distribution and marketing processes. It was originally developed in England and it is based on the analysis of size, location and frequency of knots in the wood pieces. These deficiencies affect wood mechanical properties. The mechanical classification method experimentally measures the module of elasticity in bending (Ef) and relates it to allowable bending, compression and tension stresses. The process is particularly suitable for joists, rafters, stairs and structural walls. Pieces mechanically rated are designed for spans up to 4.80 meters with an average moisture content of 12%. Even though it is impossible to fully compare the properties of different wood species used in Europe, Canada, and Chile, it is possible to compare strength resistance and humidity grades defined by each code. Chilean softwood standards are low compared to European and Canadian standards (Figure 18). In order to develop prefabricated timber panels, further research is needed to establish the implications of low-grade timber in the manufacturing of these elements.

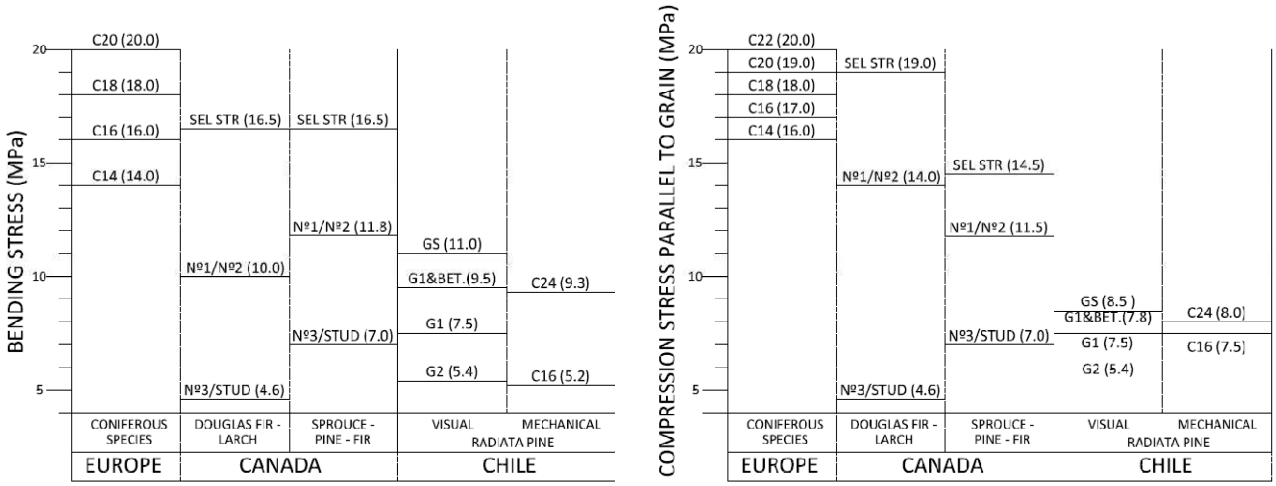

Figure 18: Admissible bending stress and compression stress parallel to the grain for coniferous species in Europe, Canada and Chile according to local codes. Sources: (CLSAB, 2004; Hanhijärvi et al., 2005; INN, 2006)

4.2 Manufacturing Feasibility

Timber as a light-weight building material has a unique potential to develop prefabricated systems. Its application as manufactured components in the first wood buildings have reduced costs and improved building standards and is considered as one of the major break points in the story of architecture (Bergdoll & Christensen, 2008).

In the early 20th century, influenced by industrialization, architects saw in the possibilities of prefabrication and mass production a solution for housing both profitable to the manufacturer and inexpensive for the customer. This rationalized model led to a boom of patented prefabricated systems. Wood frame panelized houses were common by 1940's in Europe and North America. The high point of prefabrication was the "General Panel System" by Wachsmann and Gropius from 1941 to 1952 (Figure 19). They developed a patented system composed by 10 different types of wooden structured panels with steel wedge connectors with no predefined design that allowed flexible arrangements. The most innovative feature was that the same panels could be used for floors, ceilings or walls. This condition limited the number of components of the system and increased the design flexibility. However, the manufacturing process could not provide the proper tolerances for the system to work (Bergdoll & Christensen, 2008).

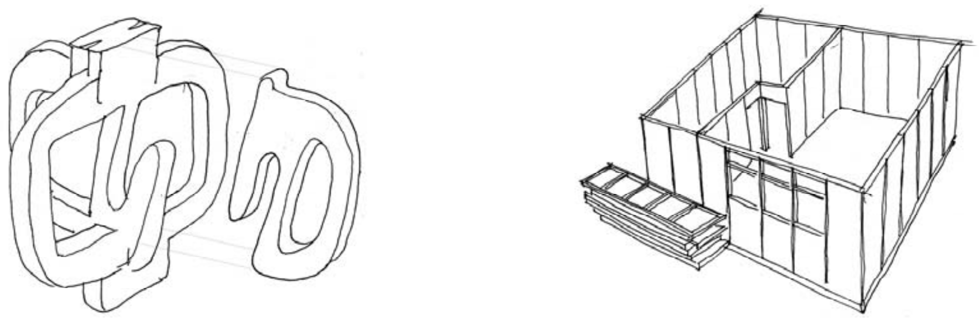

Figure 19: "General Panel System" by Wachsmann and Gropius (1952). Left: steel architectural joints. Right: construction process. Source: (Bergdoll & Christensen, 2008)

Thus, in small housing projects the platform frame system gained cultural acceptance and prevailed due to its design flexibility, economy and simplicity in manufacturing.

In the case of large structures, engineered wood products represent one of the major developments in the industry. Over recent years, building methods using diverse wood products have emerged as an alternative to manufacturing customizable panels. Among the possibilities of massive timber systems, the most common are Cross Laminated Timber (CLT), Laminated Veneer Lumber (LVL) and Laminated Strand Lumber (LSL). The development of these products has encouraged the design of larger structures using prefabricated methods that differ from the platform frame system. These cases have opened the possibilities of using wood as a feasible alternative to other traditional materials in construction (i.e. steel and reinforced concrete) in larger buildings.

These elements have been developed to allow for economic manufacturing and efficient prefabrication of components. This has broadened the range of usable raw materials, including plantation fiber and previously underutilized species (de la Roche et al., 2003). The components are manufactured under high standards in a controlled environment and are only installed on site, reducing labor and on-site costs. New fabrication tools also allow fabricating mass customized components, where different elements maintain the same standards. In addition, the limited cost of identical prefabricated elements broadens manufacturing and design possibilities.

The way to conceive wood-based architectural project is no longer based on sawn timber or on repetition of standard prefabricated component parts. Currently, the wood building process is based on customizable semi-finished products with a high grade of prefabrication and short construction periods.

According to Deplazes (2005), the basic element is no longer a linear member, but a slab; and any project can be dissected in bidimensional prefabricated planes that are installed on site just like a cardboard model. This methodology can be applied to designs of various scales as engineered wood products can be manufactured in a wide variety of sizes. Today, production processes allow prefabricating panels of almost any dimension. Prefabrication processes allow for precise manufacturing, better finishes and lower fabrication time. However, transportation and transportability are limiting factors when defining the size of prefabricated components. Panels can be up to 20 meters long and 4.8 meters wide but transport constraints normally govern panel size. A maximum length of 13.5 meters and width of 3 meters is generally considered practical (TRADA, 2009).

The possibilities of mass customization provide a new-generation of off-site production that fit this manufacturing model and reconstitute the relation between designing and making. According to Falk (2005) there is a contradictory relation between the joints and the size of the element in the process of prefabrication. On the one hand, the modules should be as large as possible to minimize the number of joints. Joints represent weak areas in the structure, thermal bridges and result in higher building costs. On the other hand, smaller components allow design optimization and flexibility because of increased combination possibilities and adaptations. Also labor, is optimized due to a lower number of operators needed during the assembly process.

Beyond the architectural possibilities and restrictions of this particular design approach, the fundamental difference with other prefabricated systems throughout history, is that the customizable configuration of panels can be labeled as an open system (Grohe, 1995), that allows great flexibility of forms and combination with other materials and construction systems.

To achieve this goal, it is necessary to combine the precision and speed of prefabrication with great design flexibility in the same production process. The industries developing this technology have opted for the use of digital manufacturing tools and the concept of mass customization that allow developing different elements without altering the production line or manufacturing periods. Thus, in the northern hemisphere since 1995, the development of prefabricated panels and mid-rise structures has exhibited exponential growth, and today it is common to find 6-storey buildings fully or partially structured in timber panels.

However, in Chile, the manufacture of prefabricated construction elements has not massively incorporated the use of digital technologies. Thus, a decisive factor to determine the feasibility of prefabricated components in the local context is the significance of the labor cost in the entire construction process. For the last 25 years, the labor cost in Chile has steadily increased. More specifically, the skilled labor costs have increased significantly compared to non-skilled labor (Figure 20).

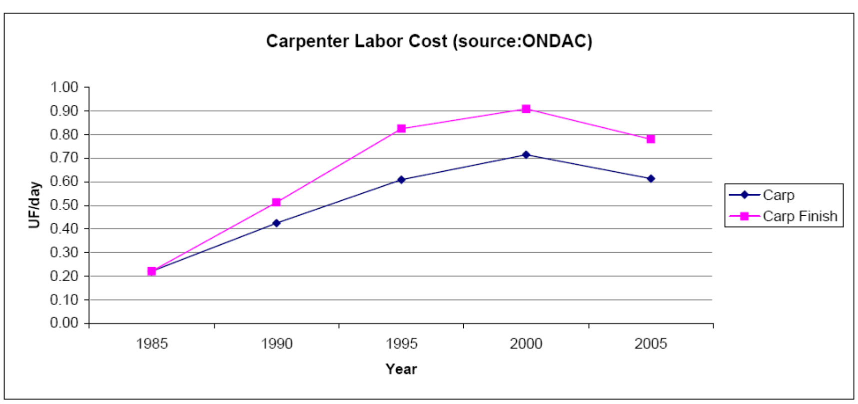

Figure 20: Carpenter Labor Cost in Chile (1985-2005). Source: (ONDAC, 1990, 1995, 2000, 2005)

Beside the increase in labor cost, since 1995, in Chile, material cost has diminished and the cost of labor has become more significant in the total building cost. For example, in 2005 labor cost represented 65% of the total cost of timber roof structures while in 1995 the cost only reached 42% (

Table **2**). The implementation of a prefabricated system that reduces labor cost can have significant implications in the building process. According to construction experiences, a standard mid-rise housing building designed with prefabricated panels advances at a rate of one storey per week (Oberholzer, 2012). This time reduction can be translated in significant building costs reductions.

Table 2: Timber Roof Structure Construction Cost in Chile (1995-2005) Source: (ONDAC, 1995, 2005)

	1995		2005	
	US$/m2	%	US$/m2	%
Labor	12.0	42.8	10.9	65.6
Building Materials	16.1	57.2	5.7	34.4
Total	28.1	100.0	16.6	100.0

4.3 Market Feasibility: Wood Perception by Users

Market research helps to recognize the feasibility of introducing timber systems in the Chilean context. The research conducted by Collect[1] identified needs and possibilities for the use of wood in housing according to impressions by users and developers. Interviews with 560 users and 20 developers in the center and in southern regions of Chile that are characterized by Mediterranean and rainy climates were conducted. The research was based on the qualitative properties of wood building material.

Focus groups consisted potential buyers of affordable housing unit ranging from $ 70,000 to $ 115,000. Results show a preference for massive construction systems and brick masonry as the preferred building material. This phenomenon is usually attributed to the strong influence of Spanish settlers and stone-

[1] Market Research submitted to "Centro de Innovacion y Desarrollo de la Madera" (Wood Innovation and Development Centre) (CIDM) of the Catholic University of Chile as part of the Research and Development projects D03i1020 and D06i1034 of the Sponsor and Development of Science and Technology Funds (FONDEF).

masonry building traditions. However, only 6% of users argue strength of wood structures as a main concern. Timber buildings are usually linked to second homes or social housing, as they are associated with low-quality or "rustic-looking" housing. Wood was also related to degraded exterior finishes and rotted interior finishes in bathrooms and kitchens. Users also perceived wood as an extremely combustible material (43%) that attracts pests and insects (36%).

As positive aspects noted by users, wood is appreciated for its aesthetical finishes (30%) and cozy conditions (40%). Its flexibility is suitable for renovations and expansions. Users noted timber as a system with good seismic performance; its lightness minimizes risks in case of a collapse. Also they are familiar with the use of timber in developed countries but they argue that related technology is not available in Chile (Figure 21).

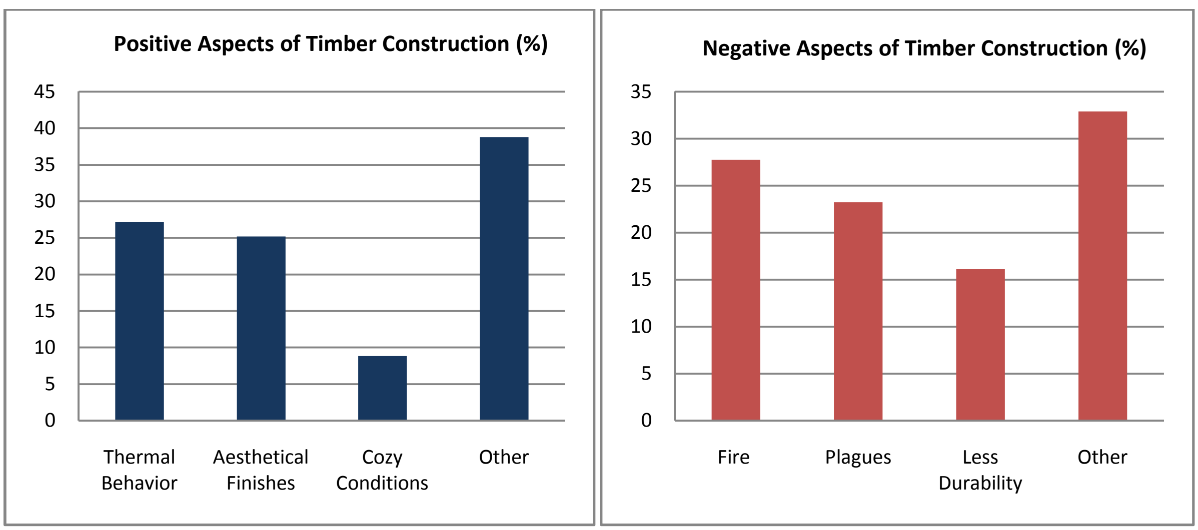

Figure 21: Use of wood in housing according to impressions by users. Source: (Collect, 2005)

The market research shows a preference for the use of massive construction materials such as concrete and masonry. According to the results of the report, it is necessary to explore new applications in the use of wood that expand the possibilities of the material and its placement in the local market.

Users recognize wood as a low-standard material due to the associated imaged with emergency housing and poor quality constructions. However, users still have a romantic and out of date conception of the material. The main attributes identified corresponded to aesthetical concepts and the main disadvantages of fire safety and plagues. Users are not aware of the updated fire safety measures and manufacturing standards.

4.4 Structural Performance

Chile is a country located in an active seismic area and has a high exposure to natural disasters. In the last 50 years the country has suffered seven earthquakes over 7º in the Richter scale and at least three of them with devastating effects on its population and buildings (Table 3). Based on these experiences, structural codes and standards have been constantly redefined in order to achieve a proper seismic behavior of the buildings.

Table 3: Recent earthquakes in Chile Source: (Ministerio de Planificación et al., 2010)

Earthquake Year	1960	1985	2010
Magnitude (º Richter)	9.6	7.7	8.8
Casualties	6,000	177	521
Victims	2,000,000	979,792	2,000,000
Destroyed Houses	45,000	142,489	200,000
Disaster Area (km^2)	166,220	48,186	131,006
Total Damage (US$ Millions)	3,089	2,106	30,000

The structural principle of timber construction differs from other traditional building systems. Wood has a high strength to weight ratio and, therefore, wood buildings tent to be lighter than other building types. The lightness of the structure reduces the seismic loads, and wood buildings consequently have more flexibility under seismic loads than reinforced concrete or masonry structures.

Numerous wood joist and stud connections and attachment of sheathing and finishes provide redundant load paths in the event of seismic forces. In platform frame and panel systems there are numerous small connections rather than few large-capacity connections. If one connection is overloaded, its share of the load can be picked up by adjacent connections (Canadian Wood Council, 2003).

Wood structures have also proven to resist natural disasters. Centuries of building tradition in wood have shown that timber structures are less susceptible to destruction by hurricanes and earthquakes (Tonks & Chapman, 2009). Researchers have analyzed the behavior of wooden residential structures after earthquakes such as the one in Kobe, Japan in 1995, which registered 6.9 on the Richter scale and the 7.2 earthquake in Turkey in 2011. Both cases emphasize the excellent seismic behavior of wood buildings; almost no timber structures collapsed due to these earthquakes. Damage reports in the case of North America also emphasize the low mortality occurred in wooden buildings during earthquakes (Table 4) (Canadian Wood Council, 2003).

Table 4: Performance of wood-frame construction in earthquakes. Source: (Canadian Wood Council, 2003)

Earthquake	Richter Magnitude	Aproximate No. of Casualties		No. of Platform Frame Wood Buildings Strongly Shaken (estimated)
		Total	In Failures of Platform Frame Wood Buildings	
San Fernando, CA, 1971	6.7	63	4	100000
Edgecumbre NZ, 1987	6.3	0	0	7000
Loma Prieta CA, 1989	7.1	0	0	50000
Northridge CA, 1994	6.7	60	20	200000

Within the wide variety of timber construction systems, it is possible to classify construction systems according to their general features and structural behavior. We distinguish timber frame, balloon frame, platform frame, panel construction, log construction, frame constructions (Figure 22).

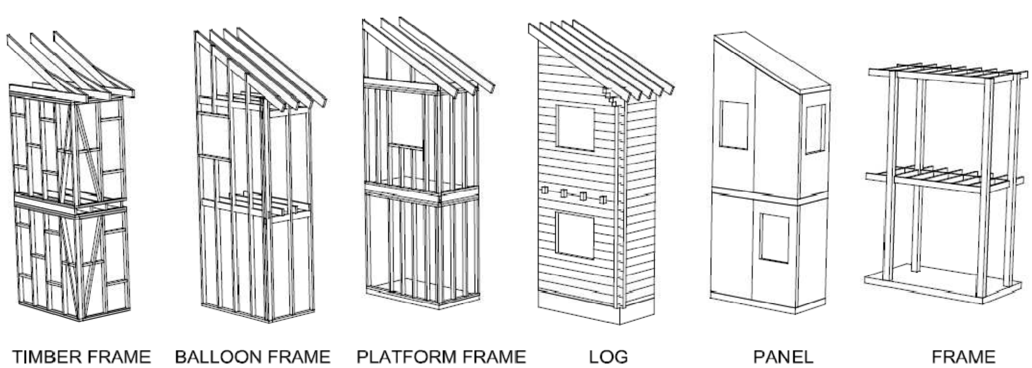

Figure 22: Classification of timber constructions systems. Source: (Deplazes, 2005)

Wood panels have particular design conditions according to their structural performance. As a plate system, components are planar elements. Structural behavior of those elements depends on the shape, location and orientation of the panels. Usually, buildings based on shearwall structures have a suitable response under seismic loads. Panels used as structural boards provide vertical and lateral stability. Timber systems achieve this performance through the use of massive timber or wood frame panels. Massive timber system panels create shearwalls and diaphragms that effectively resist seismic lateral loads; meanwhile wood-frame systems include structural panels (plywood or OSB) that act in combination with studs and joists to create the same buffering effect. Thus, it is possible to identify two different panel alternatives according to their constructive and structural considerations:

a) thin panels composed by load bearing ribs and rigid shear planks.

b) massive wood panels.

a) Thin panels are based on the light timber frame tradition. Using similar configuration as platform frame techniques, the system includes prefabricated panels that traditionally have been used in low-rise buildings. Insulation is located inside the panel and can be installed during the prefabrication process or on-site. Recently, due to code changes that allow higher timber buildings, the system has been tested to improve its structural performance.

There are different modular examples depending on dimensions and structural performance. Systems like Steko and Lignotrend (Figure 23) fulfill all structural, insulation and fire protection requirements through prefabricated timber components.

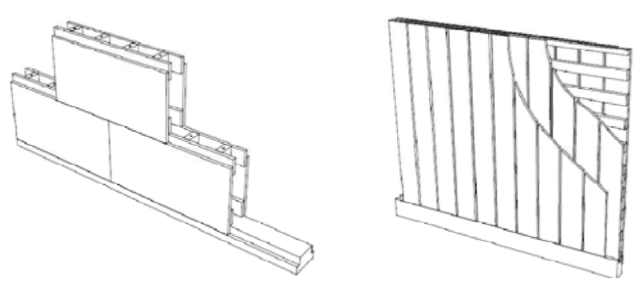

Figure 23: Steko (left) and Lignotrend (right) systems are prefabricated timber systems available in the European market. Source: (Deplazes, 2005)

One interesting case is the Ribbed Panel System (RPS) developed in Switzerland by Pius Schuler since 1997. The system is composed of a set of parallel ribs glued against a structural board that result in a compact solution of a load bearing wall with shear rigidity and vapor barrier (Figure 24). The system is based on factory-produced components; however, no carpentry firm has yet specialized in the standardized production of RPS buildings.

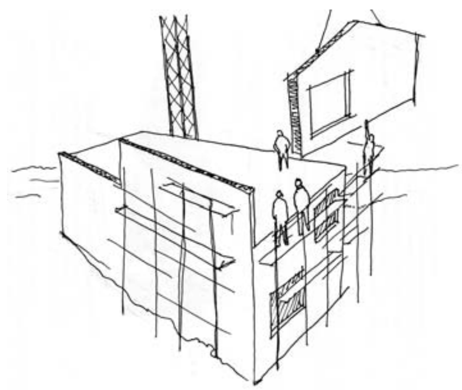

Figure 24: Ribbed Panel System house during construction. (Bearth & Deplazes architects, Sumvitg, Switzerland, 1998). Source: (Deplazes, 2005)

b) Massive wood panels are engineered for strength through lamination of various layers. In this case the load bearing capacity, shear rigidity and vapor barrier of the envelope are part of the same element. Good thermal insulation, good sound insulation and a fairly good performance under fire conditions are added benefits that come as a result of the massiveness of the wood structure (Mohammad et al., 2011). Developers in the Northern Hemisphere have used digital fabrications tools to manufacture different components at no extra cost. Generally insulation is located in the exterior side of the panel and installed on-site. Layers of massive timber panels can be glued, nailed or dowelled. More common alternatives available in the market today are:

- Cross Laminated Timber (CLT) panels made of several layers of sawn timber set at 90 or 45 degree to each other. Panel dimensions can be up to 4.8 meters wide, 20 meters long and 300 mm thick (Deplazes, 2005).

- Laminated Strand Lumber (LSL) made from a matrix of thin chips. Panel dimensions can be up to 2.4 meters wide, 20 meters long and 89 mm thick.
- Laminated Veneer Lumber (LVL) made from thin laminations of wood. Panel dimensions can be up to 2.4 meters wide, 20 meters long and 89 mm thick (mgb ARCHITECTURE + DESIGN et al., 2012).

Despite the large variety of timber panel products available on the market, so far only two systems applied to mid-rise structures have been tested for seismic resistance on a full scale shake table: Midply and Cross Laminated Timber (Figure 25).

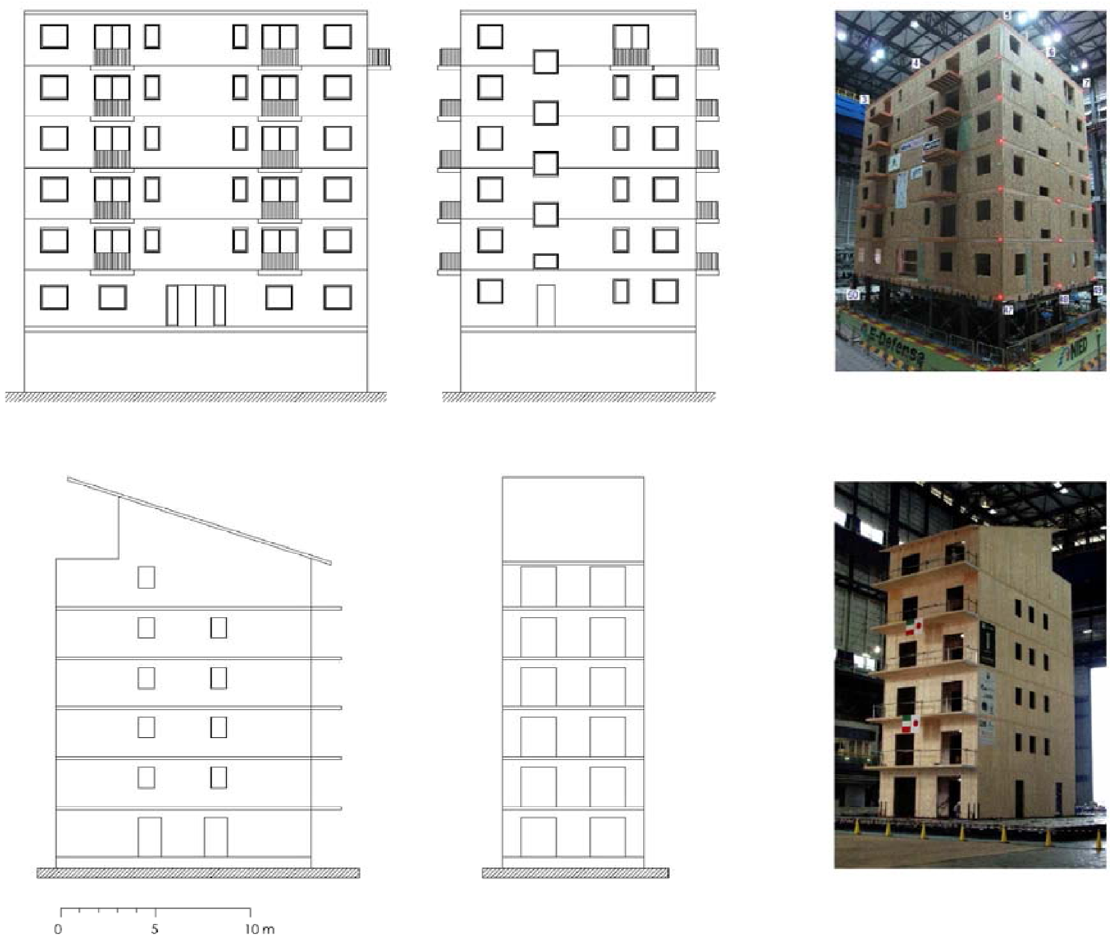

Figure 25: Left: Earthquake shake table test for a 6-storey wood frame building, Japan, (Colorado State University & Simpson Strong-Tie, 2009). Right: Earthquake shake table test for a 7-storey CLT building, Japan, (IVALSA, 2007). Images Sources: (FPInnovations, 2011; van de Lindt et al., 2011). Used by permission.

Midply System

In 2009 NEESWood and the Simpson Strong-Tie Company tested a full-scale 6-storey platform wood frame building on a shake table in Miki, Japan. Test results for a small and a larger earthquake showed moderate and acceptable performance respectively[2], but better than expected results in both cases.

Two double-Midply shear walls were installed in the building from the first through the fifth storey as traditional shear walls were not adequate to provide the necessary lateral load resistance for the building while maintaining architectural requirements (Varoglu et al., 2007).

Midply walls have been developed mostly in British Columbia, Canada, where code modifications have encourage research on new timber systems applied to mid-rise structures. On April 6, 2009 the new BC Building Code was approved. The modification increases the permitted building height of residential wooden structures to up to six storeys or 18 meters.

Among the considerations which affect structures in going from 4 storey buildings to mid-rise structures are increased lateral loads, increased environmental loads on building envelope assemblies, increased structural mass of wood affecting such items as glazing and insulation and enhanced requirements for fire suppression systems. Using traditional timber systems, it is not possible to develop structures that meet the requirements for such heights.

Implementation of Midply in the manufacturing process does not require major changes in the production line. The use of standard wood and joints makes this system suitable to the local building tradition. However, it has not been implemented in the Canadian design codes. This condition has strongly limited the use of the system.

Currently there are no plants producing prefabricated Midply panels in Canada. Currently, the main developer is a research institution. FPInnovations has extensively researched on the structural

[2] The response of the building during the smaller earthquake resulted in only hairline cracking near openings in several story levels. The larger earthquake resulted in a larger response in excess of 1% inter-story drift with some crack propagation around wall openings (Varoglu et al., 2007).

performance and construction details of the system and published papers detailing the shear capacities of the system (Varoglu et al., 2007). In 2001, the first building, in which Midply walls were used, was built. The Winslow Commons Building is a 4-storey residential building located at the University of British Columbia. Midply shearwalls were used in all corridor and party walls.

Cross Laminated Timber System

In 2007, Ario Cecotti of IVALSA (Italy) with Japanese partners[3] used a 7-storey building structured in cross-laminated timber (CLT) panels for full-scale earthquake test buildings in Japan. The Kobe Earthquake was simulated as the most destructive to date; the building passed 14 tests in a row with no damage to the panels; only joints were affected in the last iteration of the test (Quenneville & Morris, 2007). Currently, Cross Laminated Timber is the most significant case of massive timber panels in Europe. This construction system has been developed since mid 1990's and has become a well-established building alternative in central Europe. Fifteen main CLT productions sites can be found in Europe. Austria is the leading country with a production of 76.000 m^3 per year and the presence of KLH Massivholz GmbH as the world largest CLT producer (Schickhofer, 2011).

The implementation of CLT products and systems in Canada is recent. This development is strongly supported by the constant research carried out over recent years. The main researchers in the area are the Department of Wood Science Studies from the University of British Columbia and FPInnovations. Investigations focus on various issues ranging from structural performance to the environmental impact. These technical aspects aim to validate the system against other constructive alternatives.

In 2011, the first CLT Canadian conference took place in Vancouver where the launch of the “CLT Handbook” by FPInnovations set a comprehensive reference for design and construction support on CLT systems. This peer-reviewed handbook provides technical information on Cross Laminated Timber

[3] The National Research Institute for Earth Science and Disaster Prevention NIED, the Building Research Institute BRI, and Shizuoka University.

elements in areas such as manufacturing, structural design, seismic performance of buildings, connections, duration of load and creep factors, vibration performance of floors, fire performance of assemblies and acoustic performance of assemblies.

The use of CLT panels in Canada is gaining interest in the wood industries and with contractors because its structural performance allows CLT structures to meet code requirements for mid-rise buildings. Currently, there are three significant CLT manufacturers in Canada: Structurlam Products located in Penticton, BC[4], Canadian Sustainable Timber (CST) Innovations in New Westminster[5] and Nordic Engineered Wood in Montreal, Quebec[6]. A common characteristic of these manufacturers is that they have previously produced other engineered wood products such as Glulam. This condition minimizes the risks of investment, facilitates the implementation of manufacturing processes and allows the design of combined structures solutions in CLT with other timber systems. However, the implementation of the system in the market is still slow. In the case of Nordic, production of CLT panels started 3 years ago. Although the plant capacity is 80,000 m^3 per year, the current production only reaches 10,000 m^3 per year (Oberholzer, 2012).

This thesis focuses on the application of CLT and Midply systems to the Chilean context. The research assumes that these systems will respond better to local conditions of the case of study because of three main features:

- Development as open systems that can be easily adapted to various design layouts.
- Possibilities to be prefabricated allow for improved manufacturing standards. Traditional timber productive processes can be easily modified to manufacture these new systems.
- Seismic performance that has been tested using full-scale prototypes.

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[4] http://www.structurlam.com
[5] http://www.cstinnovations.ca/
[6] http://www.nordicewp.com

4.4.1 Manufacturing Features

Both CLT and Midply panels can be fully prefabricated and installed on-site. Components are lifted with a crane and assembled using lightweight power tools. These two features facilitate the quick erection time, especially in mid-rise buildings (Figure 26). Detailed budget comparisons by FPInnovations CITA and Life Cycle assessments by TRADA (2012) show that a building using contemporary timber building techniques has a lower environmental impact, is quicker to assemble and cheaper than traditional concrete construction. The building process differs due to dry connections and joints in timber that require no wet trade and are easily handled. According to building experiences in Canada (Oberholzer, 2012), a team of 4 workers can assembly one storey in approximately one week. Thus, a 4-storey building can be erected in one month.

Figure 26: Prefabricated panels and dry connections allow a quick and cheap installation on-site. Photograph credit: KLH, www.klh.at Used by permission.

Using CLT panels does not include site-cutting of timber elements. An adequate coordination must been undertaken at the design stage (TRADA, 2009). Some manufacturers such as Nordic Engineered Wood rely on software such as “Cadworks” for the integration 3-D design documents with technical 2-D manufacturing drawings.

Midply panels can also be fully prefabricated; however, on-site modifications can be easily made using conventional tools. The Midply panel system is better suited for expansions and renovations. When construction takes place in dense urban areas, prefabricated systems result in a relatively low level of noise and traffic disruption. This is an important advantage where the impact on neighbors needs to be considered.

4.4.2 General Structural Considerations

The structural layout of both CLT and Midply systems is based on the platform frame system. This means that each floor slab lies on top of storey-high walls. The main structural disadvantage of this system for mid-rise and high-rise buildings is the effect of vertical loads on the lower storeys. Sole plates of panels located in lower levels are subject to high compression stresses perpendicular to the grain of wood, thereby producing a crushing effect that limits the building height. The same effect occurs in CLT buildings where floor slabs are located between wall panels. Lower floor slabs receive high-loads from upper storeys and high-compression stresses perpendicular to wood grain.

Today, up to 9-storey high CLT buildings have been built. TRADA (2009) developed an example of a 12-storey CLT residential building designed to meet structural and serviceability criteria according to Eurocode 5. The 9 m x 9 m structure considered the feasibility of 125 mm thick floor and external wall panels and 135 mm thick internal wall panels. However, the study did not considered seismic loads and stated that further checks are needed for bearing stress on cross-grained elements such as sole plates, floor panels and fire resistance. Popovski (2012) estimates that the maximum height for these structures cannot exceed 15 storeys.

For the further development of timber high-rise structures, it is essential to consider systems that orientate compression stresses parallel to the wood grain of the component. One alternative is to apply a structural layout based on the balloon frame system where vertical elements are continuous along the structure and floor-slab panels are suspended from wall panels.

Design of panel-based buildings must fulfill calculation requirements (static equilibrium, serviceability, robustness) for the whole structure, but also for each single panels and particular joints. Panels can have bending and shear deformations due to external loads. Also joints must ensure proper connections between panels to prevent tilting (Figure 27). All these panels are typically used as load-carrying plate elements in structural systems such as walls, floors and roofs. Thus, structural design of timber panels is directly related to the direction and magnitude of loads acting on the element.

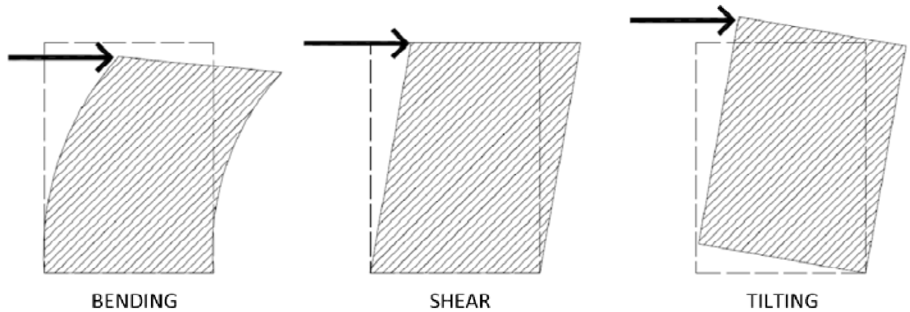


Figure 27: Bending deformation, shear deformation and tilting (connectors slip) due to lateral loads applied on a panel.

Timber panels can be considered as structural planar elements as their height and width are much more resistant to loads than their thickness. In other words, both CLT and Midply panels are very resistant to axial loads to the main face of the panel, but weak to perpendicular loads. The two main aspects to consider in structural design of timber panels are:

- Dimensioning of the element itself, i.e. its height, width, thickness and materials used.
- Design of reinforcement elements, joints or connectors between panels.

Structural behavior of wood panels mainly depends on the orientation of the panel. This thesis analyses the structural behavior of Midply and Cross Laminted Timber systems for wall and floor panels. The performance of inclined surfaces (e.g. roof components) is a combination of both panels. Also the analysis considers the design requirements for connectors between structural panels.

a) Floor Panels

The role of floor panels is to carry and distribute dead loads and live loads along their surface to the supporting walls. In building layouts where walls are vertically continuous elements, floor panels only carry their own loads. In these cases, their location in the height of the building is irrelevant for structural calculations. Therefore, the slab span is the main design consideration for structural design. In the case of walls, main loads are gravitational and vertically oriented. However, structural design usually considers lateral loads (wind loads or seismic loads) as main restrictions for mid-rise buildings.

Structural and architectural design must consider the shrinking effect for timber mid-rise structures. The shrinking effect in timber panels is the result of vertical loads in the long term and compression strength parallel to the grain of the wood. The effects of vertical loads and compression have been discussed extensively in the case of medium-rise buildings. According to Augustin (2008), the overall magnitude of shrinking in mid-rise buildings can be larger than typically noticed in low-rise timber buildings. The worked example of a 12-storey CLT residential building developed by TRADA (2009) estimated a long-term vertical displacement of 3.1 mm per storey. A research by the University of Växjö (Xiong Yu et al., 2009) measured the vertical displacement of the Limnologen building. This 6-storey building is completely structured in CLT wall and floor panels. The maximum vertical displacement measured was 21 mm (3.5 mm/storey).

Architectural design must consider that level variation could be significant. Usually the joints of timber structural elements with non-structural elements (e.g. partitions, flashings, doors, windows, etc.) or other structures with different structural behavior (e.g. reinforced concrete or masonry) require special detailing (Figure 28). The uses of reveals or adaptable joints are good practices to absorb a dimensional variation from 3 to 5 mm.

Figure 28: Displaced flashing due to the shrinking of a timber structure next to a masonry finish. Source: (APEGBC, 2009). Used by permission.

b) Wall Panels

Structural design of wall panels considers the effect of vertical loads and lateral loads. Wall performance considers material properties (e.g. module of elasticity) and dimensional configuration properties such as the slenderness ratio.

Vertical loads are composed by the weight of the own structure and live loads such as occupancy and snow loads. As noted above, in mid-rise buildings walls located in the bottom floors of the structure are subject to greater loads. Under high compression loads panels will tend to buckle resulting in a bending moment or torsional deformation depending on the distribution of the load.

Wind load and seismic loads can be considered as the main lateral loads acting on wall panels. In the case of timber panels, shear-plates resist lateral stresses or massive panels themselves perform a shear-plate action (Falk, 2005).

In the case of floor slabs or roof elements dead loads are applied perpendicular to the face of the panel causing high-shear stresses in the element.

c) Connectors

All timber structures can be considered as a combination of individual elements. Panel-based structures minimize the use of joints due to the use of large prefabricated elements. Usually connectors are located at the edges of the panels and their design depends on the function of the interacting panels. These connections can be classified as wall-wall, wall-foundation, wall-floor-wall and floor edge connections (Figure 29).

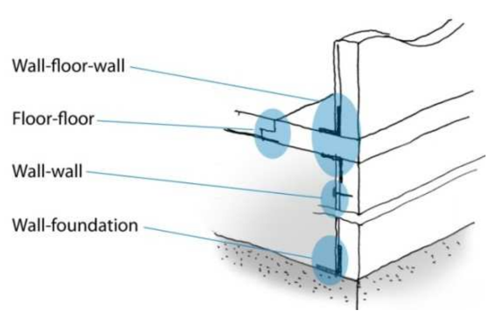


Figure 29: Types of connections in multi-storey buildings. Source: (Augustin, 2008).

Joints are responsible for maintaining the structural integrity of a building and leak-proof connections (thermal bridges, air tightness and sound insulation). Designs should also consider that connectors commonly are critical points in the building for fire safety, finishes and utilities. Efficient connectors must ensure a tight fit between individual panels and should be easy to mount to allow for quick and low-cost installation of the panels.

4.4.3 Midply System

Midply systems consist of a variation of wood frame constructions to achieve a greater load carrying capacity per unit wall length. A standard shearwall consists of a structural sheating panel fastened to a wood frame built with studs and plates. Studs are generally made of 2"x3" (38 mm x 64 mm) or 2"x4" (38 mm x 89 mm) lumber and spaced at 16" (400 mm) on centre (Figure 30).

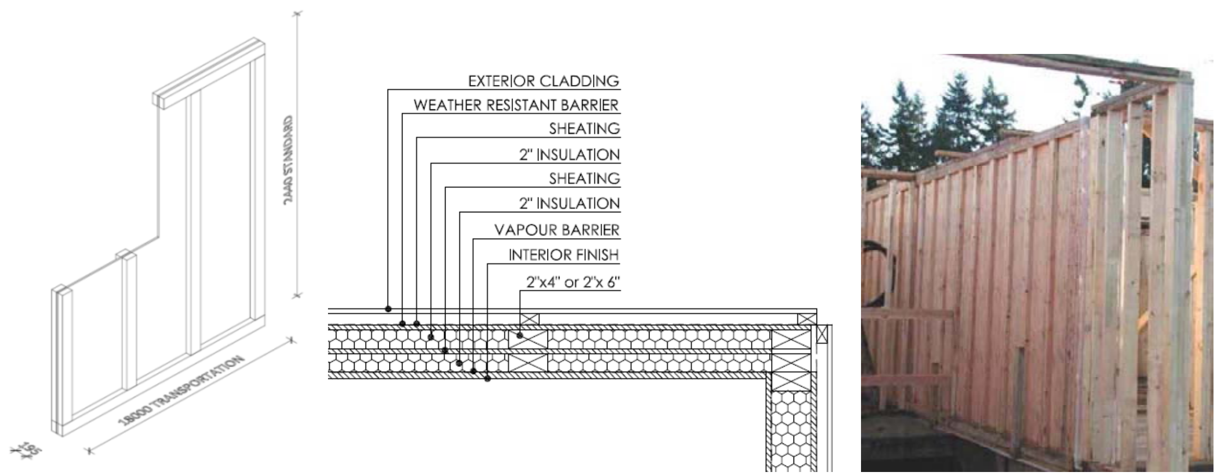


Figure 30: Midply panel. Source: (Karacabeyli & Popovski, 2010). Used by permission.

At the bottom of the wall, studs are supported on a horizontal bottom plate or foundation sill plate. At the top of the wall the studs support the horizontal double plate. Sheating is fastened to the narrow faces of the studs.

The Midply wall system consists of the same building components used in regular shearwalls but with a different arrange (Figure 31). Structural sheating is located at the wall's center with studs on both sides that generate double shear connections for a greater resistance (Karacabeyli & Popovski, 2010).

According to structural tests developed by FPInnovations, resistance of Midply walls equals three times the resistance of wood frame standard walls (Ni, Popovski, Karacabeyli, Varoglu, & Stiemer, 2007).

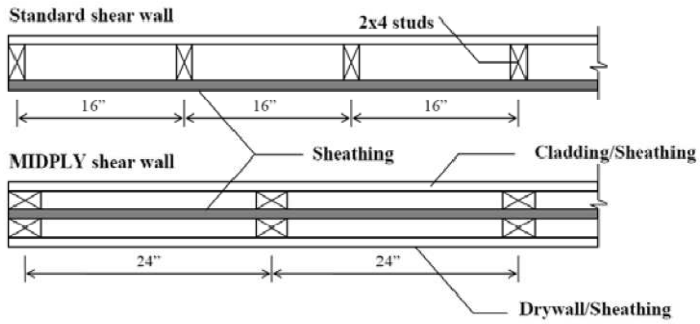


Figure 31: Left: Structural sheating located at the wall's center. Source: (Karacabeyli & Popovski, 2010). Used by permission.

In general, the structural designs of Midply buildings do not significantly vary compared to the calculations of platform frame wood buildings. Considerations detailed in the Canadian Wood Design Manual and CSA 086 can be used as reference for regular shearwalls. However, Midply shearwalls can be assigned twice the shear capacities of regular shearwalls. Higher wall shear capacity contributes significantly in the overall seismic performance of a storey and tests have shown that Midply walls are a feasible structural alternative for mid-rise platform frame buildings in seismic regions (Varoglu et al., 2007). Midply walls are conceived as an improvement of platform-frame walls for shear rigidity in areas where where shear wall length is limited by design or where large lateral loads demands are expected. Thus, this wall system is not intended to be applied in the entire building due to the high costs associated with their use.

a) Walls

Common practice for platform-frame structures suggests the use of 2” x 4” or 2” x 6” studs spaced at 400 mm on regular wall panels. Midply walls consider the same framing member, sheathing, nail size and nail spacing used in platform-frame structures. However, studs can be located every 600 mm in Midply panels. To ensure a proper performance of the Midply system, wall panels require vertical continuity in the full height of the structure. This vertical continuous configuration makes Midply walls a suitable alternative for stairwells and elevator shafts. Other elements such as cantilevers and balconies are not recommended for Midply panels.

Load bearing capacity of Midply walls is considered the same of regular platform frame walls.

b) Floor Panels

Prefabricated floor panels can be manufactured with sawn timber commonly used in platform-frame systems or engineered timber products. According to the Canadian Wood Design Manual (2010), sawn lumber used as joists ranges in thicknesses from 38 to 89 mm and depths from 89 to 286 mm. Joists of 38 mm x 184 mm spaced at 400 mm meet the conditions for a 3 m span, while joists of 38 mm x 286 mm spaced at 600 mm meet the structural and serviceability requirements for a 4 m span. For longer spans I-joist joists are commonly used in mid-rise buildings. Depths of I-joists commonly range from 241 mm to 610 mm and in lengths up to 18 m (Figure 32).

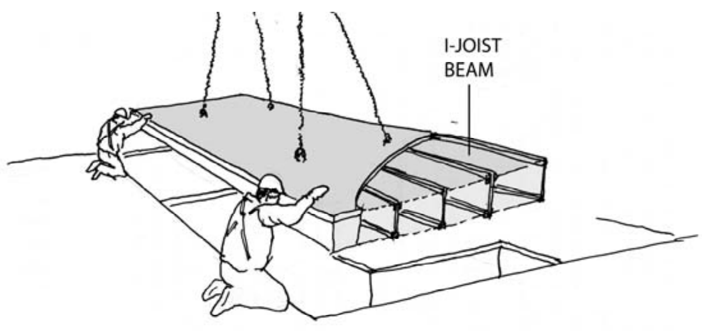


Figure 32: Structural prefabricated wooden panel using I-joist by Donaldson Timber Engineering (UK).

c) Connectors

Nails and screws are used as main connectors in the manufacturing of Midply walls. In fact, the increased shear strength of the wall is product of the interaction of fasteners and timber elements. The shear panel is located at the center of the wall between the studs. Nails connecting the panel with the wood frame work in double shear providing the increased lateral load capacity (Figure 33). Nails are located on the wide face of the studs providing more edge distance and reducing the possibility of tear out failures. Also nails going through the panels missing studs are avoided with this configuration.

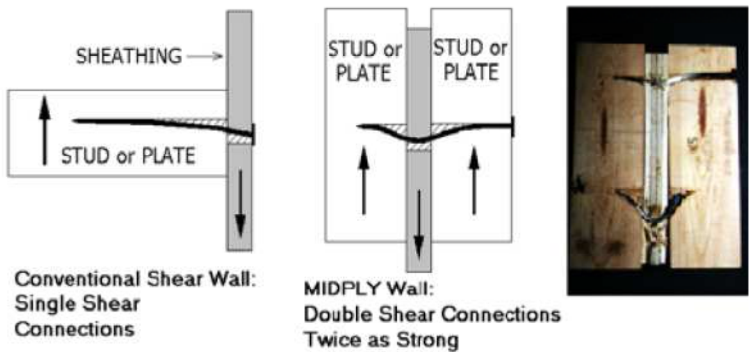


Figure 33: Scheme of the structural behavior of double shear connections at Midply walls. Source: (Karacabeyli & Popovski, 2010). Used by permission.

Fastener considerations for platform frame structures must be developed according to the Canadian Wood Design Manual and the CSA 086. However, the lightness of the system produces wind uplifting loads that undermines the proper performance of Midply walls. Steel connecting rods have been used by the light-framed construction industry to prevent uplifting stresses and to allow walls to develop their full lateral load capacities (Ghosh et al., 2006). Continuous rods are used to ensure the wall performance as a single structural element and special connectors adapt to the shrinkage of the structure compensating up to ¾” per storey (Figure 34).

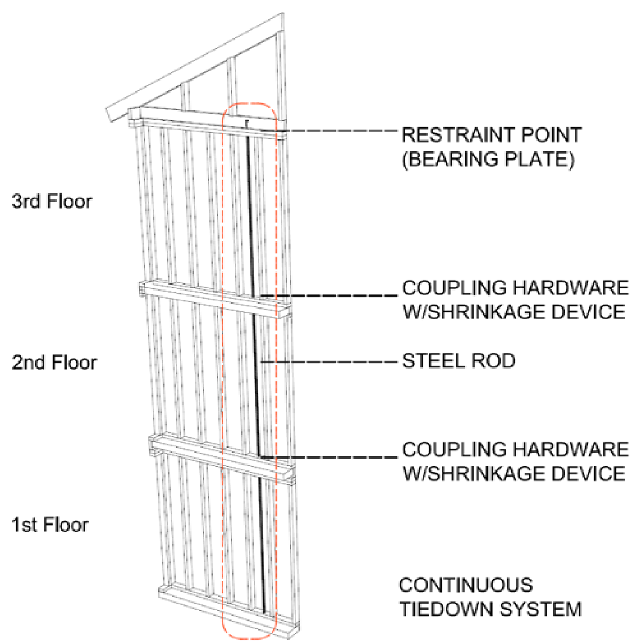


Figure 34: "Alternative Wind Uplift Restrain System" by Simpson Strong-Tie. Source: (Ghosh et al., 2006)

4.4.4 Cross Laminated Timber System

Traditionally, massive timber systems have been used wood fibers oriented in one direction only: both in vertical and horizontal applications. The main feature of CLT panels is the performance of a panel in all directions. In comparison, fibers in LVL or LSL elements are oriented in one direction. LVLs and LSLs, therefore, only span in one primary direction. CLT panels, however, can be considered as isotropic structural elements.

CLT is built up by layers of wood pieces in different directions locking each other for increased rigidity and stability. A wall thickness can be from 3 to 9 layers, normally in odd numbers to maintain element symmetry. Each layer consists of finger-joint laminated boards planed on all sides (Figure 35).

According to FPInnovations (2011) the thickness of layers can vary from 10 mm to 50 mm. European manufacturers (KLH, 2008) use boards from 19 mm to 40 mm thick. Usually, the thickness of American-produced CLT is 38 mm due to the willing of manufacturers to use standard 2”x4” (38 mm x 89 mm) dimensional lumber in the process. The uneven number of layers gives the plate one stronger direction (parallel to outer-layers grain) and one weaker direction. Layers can have varying orientations (e.g. 90º or 45º) leading to different structural behaviors (Falk, 2005).

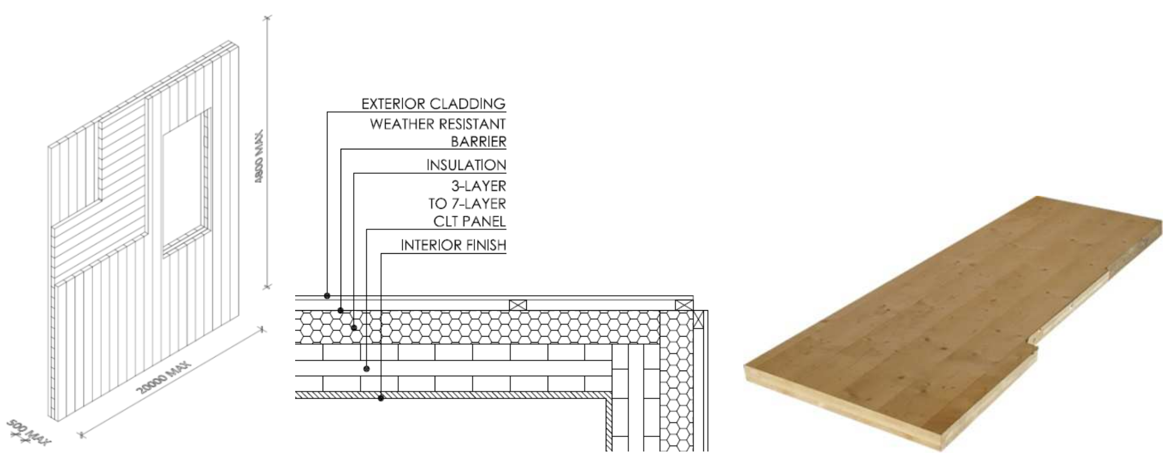


Figure 35: Cross Laminated Timber (CLT) panel. Right Image: Source (Jones, 2007)

Grade no1 or no2 wood is used in outer layers. If panels are exposed, better quality wood species can be used for a better-quality finish. In interior layers, low-grade wood (no. 3 or studs) can be used to lower costs. Test on low-grade wood on CLT panels have shown good results for span elements (Yawalata et al., 2010). Layers can be doweled (e.g. Solm, Thoma), glued (e.g. KLH) or nailed (e.g. Hundegger) to each other. Today, glues that are normally used are phenol formaldehyde (PF), phenol resorcinol formaldehyde (PRF) and polyurethane (PUR). Glues may vary depending on the manufacturer.

CNC machines used in manufacturing allow the development of different panels without altering production times. These machines have been fully incorporated in production process and usually define the maximum size of panels. As seen on Table 5, in many cases size constrictions are given by feasible transport dimensions of the panels.

Table 5: Maximum dimensions for manufacturing and transportation of CLT panels.

Source		Length (mm.)	Width (mm.)	Thickness (mm.)	
KLH		16500	2950	500	(1)
Leno		20000	4800	300	(2)
FPInnovations		18000	3000*	400	(3)
Nordic		19500	2743	381	(4)
Road Transportation	No Aproval	18250	2550		(5)
	Aproval	25000	3500		(5)

* 4000 mm. – 5000 mm. are feasible in particular cases.

(1) Source: (KLH, 2008)
(2) Source: (Deplazes, 2005)
(3) Source: (FPInnovations, 2011)
(4) Source: (NORDIC, 2012)
(5) Source: (Winter, 2004)

Massive timber systems have a structural behavior more similar to concrete structures than timber frame structures due to the stiffness of their components (Malczyk, 2011). Panels have high shear stiffness and excellent performance to creep and bending stresses. However, special considerations must be taken in the connections as they assure the proper relation between structural elements. Panels are usually composed by odd number of layers with interior layers manufactured using lower grade timber. Thus, although isotropy was noted as a main feature of CLT components, panels have one strong side and one weak side. The stronger side is orientated parallel to the outer wood grain of the panel (Figure 36). It is the result of the action of an extra layer of timber and better grade of lumber.

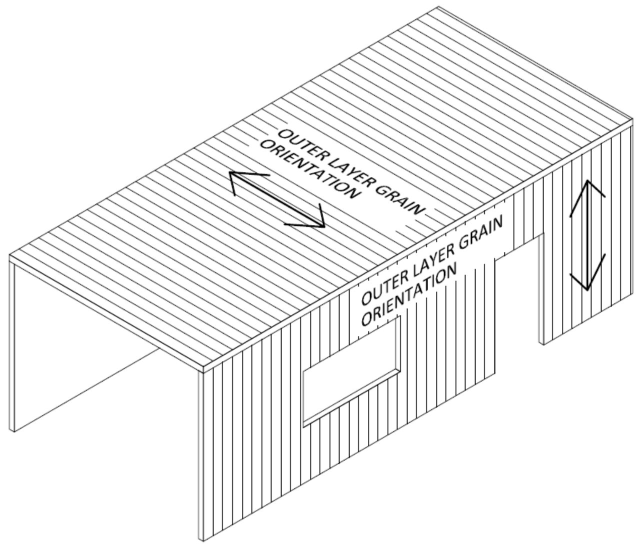


Figure 36: Strong side of CLT components in floor and wall panels.

a) Walls

Two proposed design methods for CLT wall panels are commonly used. The first one uses a truss-model that considers walls as trusses with diagonals connected through articulated joints to the lintels. The second model considers a frame-model with longitudinal and transversal beams (Figure 37). The Finite Element Model can be used for more detailed calculations (Augustin, 2008). Opening such as windows and door lintels can be calculated as beams with the dimensions of the longitudinal layers running in the direction of the opening. According to manufacturer specifications, it can be assumed that the beam is fixed at both ends if the adjoining wall pillar is wider than the height of the beam, if not it must be assumed as an articulated joint (TRADA, 2009).

Other approaches consider the method of Mechanically Jointed Columns detailed at the Eurocode 5 where walls are considered as a frame system (TRADA, 2009). Also, FP Innovations proposes design methods to calculate beams and lintels based on Simplified Design Methods for Calculating Bending Strength and the Composite Theory – k Method (Gagnon & Popovski, 2011). In most of these methods only the layers oriented parallel to the axial force are considered to carry the load. However, shear deformations can play a significant role in the calculation of the axial load capacity of the walls.

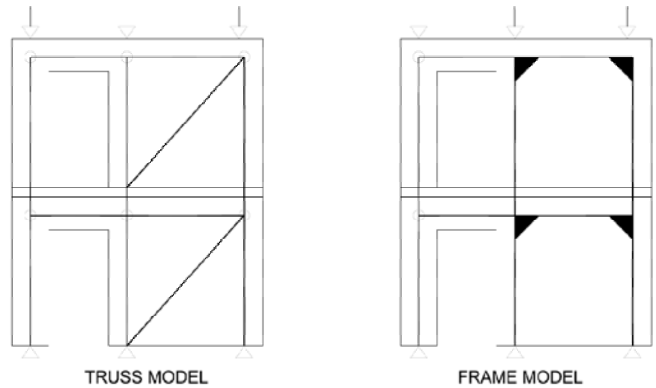


Figure 37: Modelling of a shear-wall loaded by vertical and horizontal actions by a truss and frame model. Source: (Augustin, 2008).

b) Slabs

CLT slabs present distinctive features due to their layered composition. The structural deformations caused by loads on CLT slabs can be identify as deformation and deflection due to bending and shear:

- Bending Deformation or Deflection: CLT slabs panel can be considered as a group of small beams that is perpendicularly loaded. Due to the effect of these loads, bending occurs in the same way as it occurs in a beam (Falk, 2005). According to serviceability considerations European codes admit a maximum deflection of L/300 while European manufacturers recommend L/400 in their brochures where L is the length of the slab span. Canadian structural design recommendations set a maximum deflection under live load of L/360 and total load of L/240 (Gagnon, 2011).
- Shear Deformation: Perpendicular loads applied to the layered configuration of the panel can result in two types of deformations: shear deformations are originated in the longitudinal boards in the panel. Meanwhile rolling shear deformations occur in the transversal boards of the panel.

The phenomenon of shear deformation is caused by the shear stress applied in the same direction of the element section[7] (Figure 38). For massive wood elements, shear forces depend on the interaction between the layers. More interaction allows various layers to behave as a single element while less interaction results in the independent structural behavior of the layers. In general, the shear deformation of CLT panels may be neglected for floor elements having a span-to-depth ratio of about 30 (Gagnon & Popovski, 2011).

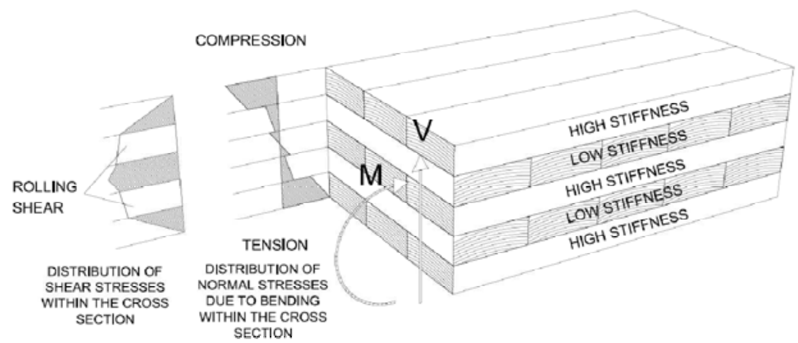


Figure 38: Stress distribution of a CLT-element with glued narrow faces of the boards loaded by a moment and a transversal force. Source: (Augustin, 2008).

Rolling shear is caused by shear stresses perpendicular to the wood grain. Differences in strengths of the wood grain are due to the tree characteristics and configuration of weaker winter layers (early wood) and stronger summer layers (late wood) (Falk, 2005). As a consequence particular layers of the cross-section, that carry loads perpendicular to the grain are stressed in tension and compression, leading to low-carrying capacities. Shear failure can be seen as a combination of two types of failure: rotation of cross layers and rolling of early wood zones (Figure 39). The "rolling shear modulus" is not a material property but can be handled as a shear stiffness characteristic dependent on structural wood parameters (Augustin, 2008). Rolling shear significantly affects the stiffness of a panel and may be

[7] According to Gagnon (2011), for softwood species G ≈ E/16 where the modulus of elasticity (E) is assumed to be 10% of the shear modulus parallel to the grain of the boards (G). The shear module perpendicular to the grain (Rolling Shear Module) is generally assumed as G=E/10.

significant in the structural behavior of CLT slabs[8] (Gagnon & Popovski, 2011). The proper interaction between the layers is also relevant for rolling shear considerations. Gaps or incorrect glueing affect the performance of the panel as a continuous element or as individual layers.

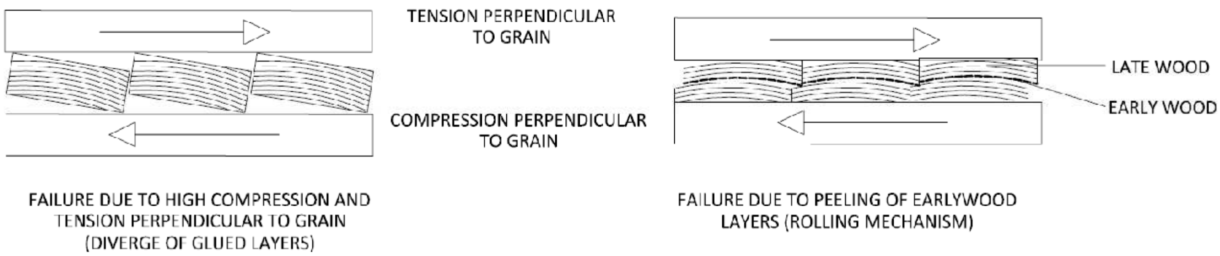


Figure 39: Failure mechanism within the cross layers of a CLT-element (macroscopic). Source: (Augustin, 2008).

For structural design, strength and serviceability criteria are considered. "Flexural stiffness of CLT panels is usually of greater interest for designers than the strength, since the structural design is mostly governed by serviceability criteria" (Gagnon & Popovski, 2011). The mains aspects to consider in the design of CLT floor slabs are bending deformation, vibration restrictions and the creep factor.

Usually floor slabs are designed as the addition of various floor panels due to their restricted dimensions. Thus, slabs cannot be calculated as a continuous element because joints between panels generate structural gaps. Connections between panels should assure continuity of the slab, but so far no connection has proven to meet the requirements.

Although loads on slabs can generate one-axis or two-axis bending depending on the length-width ratio of the panel, slabs are usually modeled as one-axis bending elements. No verification for horizontal loads, such as wind or seismic loads, are necessary because CLT floor panels are considered as stiff panels for parallel- to-the-plane loads (Augustin, 2008).

Due to the recent development of CLT panels, different approaches to the structural design of slabs have been used. Structural design methods for slabs consider the Efficient Module of Elasticity (Eeff)

[8] Rolling shear strength varies between 18% to 28% of parallel-to-grain shear values (≈ 0.3 to 0.6 MPa) (Augustin, 2008).

and Efficient Module of Rigidity (Gi eff) as material properties. This information is known for standard materials such as concrete or steel. However CLT is not an homogeneous material as the wood grain is uneven-orientated in two directions. Structural calculations base on other structural methods are an approximation to determine the value of Eeff and Gi eff. The most commonly used are:

- Mechanically Jointed Beams Theory (Gamma Method): Based on Annex B of Eurocode 5 (EN 1995:2004). This method takes into account the rolling shear stiffness (GR) of the cross layers using “imaginary fasteners”. Longitudinal layers are taken as beam elements connected with “imaginary” fasteners that have stiffness equal to that of rolling shear deformation of cross layers. Only layers acting in the direction of loading are used. Recommended for 3 and 5 layers CLT panels.
- Composite Theory (k Method) based on a theory used for plywood that considers the stiffness of all layers. Compositions factors (ki) are defined for certain loading configurations. Effective values of strength and stiffness are calculated using a composition factor ki.
- Shear Analogy (Kreuzinger) is based on CLT panels separated into two virtual parallel beams. This method considers different modulus of elasicity and shear modulus of the single layers in both directions. Shear stiffness and shear deformation are also considered in calculations.

The first two methods are recommended for span-to-depth ratio> 30 as the shear deformation has no greater significance. The Shear Analogy method is recommended for panels with a span-to-depth ratio < 30 because it is the most comprehensive analysis. Usually residential buildings consider layouts with spans no longer than 5 meters.

Figure 40 shows a comparison of different structural design approaches applied to CLT slabs according to research organizations tests and manufacturers specifications. Thicknesses of slabs maintain a similar range with variations that do not exceed 50 mm. According to all calculation methods, a 200 mm thick 5-layer panel adjusts to the design requirements properly. Also, the comparison of CLT slabs versus reinforced concrete slabs show a better performance for massive timber slabs that can achieve longer spans.

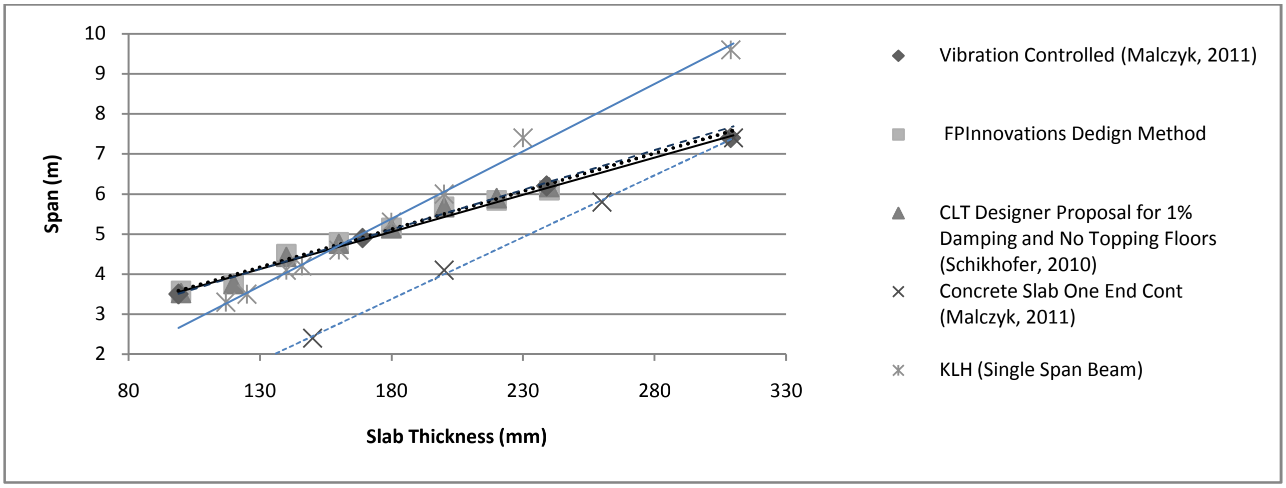


Figure 40: Comparison of structural design approaches of CLT slabs according different calculation methods and manufacturers' specifications.

c) Connectors

CLT systems consider the use of simple connectors that ensure a rapid installation of the panels on site and flexibility in design. Connectors commonly used are traditional fasteners (screws, nails), carpentry joints or plates. The role and orientation of the panels determine the type of connectors to be used.

Self-tapping screws are the most commonly used connections in CLT panels. Screws with a nominal diameter of 4mm to 12mm and length up to 600mm are available in the market. For wall panels, it is recommended that self-tapping screws exhibit a nominal diameter of 4 mm (5 mm) and length of 70 mm (92 mm). Nails must have a diameter of 3.9 mm and length from 67 to 99 mm. In many cases Glulam considerations are used as a reference for CLT calculations because the CSA 086-09 provides no guidance on self-tapping screws (Mohammad & Munoz, 2011). Alternatives like double tongue and groove joints, bolts or steel pipes have been also used in some projects with no conclusive results.

CLT panels can be considered an effective lateral load resisting system. The use of multiple connectors provides redundancy to the structure and all walls contribute to lateral and gravity resistance in the structural system. The system performs adequately under seismic loads when steel brackets are used to connect walls to floor panels. Wall panels as vertical carrying elements present high stiffness to shear stresses, so structural considerations are located in the hold-down bracket connection areas. Self-taping screws are not recommended for floor-foundation or floor-wall connections in seismic zone designs. In these cases, structural plates are used according to specification of the manufacturers (FPInnovations, 2011).

Manufacturers such as Simpson Strong-Tie and Rothoblaas have designed joints for CLT panels. Their angle brackets can be used for wall-to-floor panel or wall-to-concrete foundation connections. They are designed for high shear stresses and can be rapidly installed using standards nails (Figure 41).

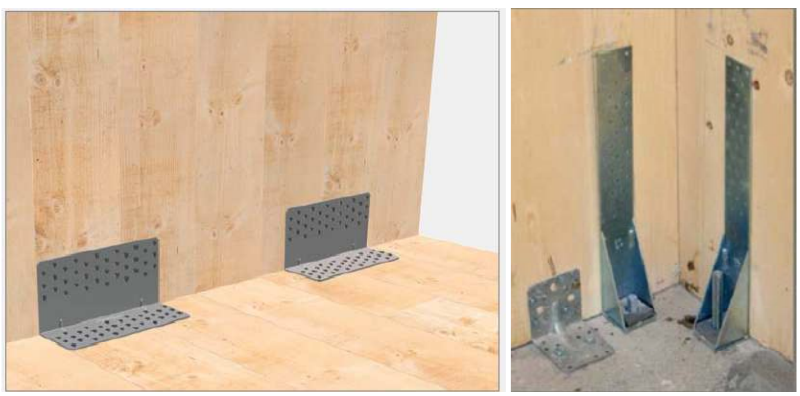


Figure 41: Angle brackets for CLT panels by Rothoblaas. Left: Titan angle bracket for shear loads. Right: WHT angle bracket for tensile stresses. Source: (Rothoblaas, 2012).

4.5 Local Building Codes and Standards

4.5.1 The Chilean Structural Code (NCh 433)

The structural design of all buildings in Chile is regulated by the code "NCh 433.Of96 (1996) Seismic Design of Buildings" and is based on the *Uniform Building Code* (ICBO 1995). According to this code, there are no height restrictions due to structural considerations in Chile. Usually, the maximum height is defined by the Chilean General Ordinance and urban planning considerations by each district. In general, a building's maximum heights are defined by sky exposure planes designed to provide light and air at street level. Currently, the NCh433 Code does not require structural calculations for buildings up to two storeys or 7 meters in height. For higher buildings, structural calculations must be submitted by a certified professional.

For the specific case of calculations for timber structures, buildings are regulated by the Chilean Code NCh 1198-2006 "Wood - Timber Buildings - Calculations". However, this code does not give information on allowable shear loads for timber-frame walls; it just provides design data for isolated elements and joints. The NCh1198 Code is currently in a revision process, and a draft of an update has been written by consultants at the British Columbia Institute of Technology (BCIT) and added to by personnel at the Chilean Timber Corporation (CORMA).

A study by the University of Washington and the University of Concepcion (Dolan et al., 2008) compared the current design provisions for timber structures available for use in the United States with those currently used in Chile. Structural design in the United States is regulated by the code "U.S. ASCE 7-05 (2005) *Minimum Design Loads for Buildings and Other Structures*". The Chilean NCh 433 Code have significant differences with United States' standards that affect the assumed relative performance of timber structures.

Table 6: Base assumptions for the seismic analysis by Dolan. Source: (Dolan et al., 2008).

Variable	U.S. Value	Chilean Value
Building Type (Light-frame 3-storey, Bearing wall system, Area < 3.000 m2, Occupancy < 100)	Type II	Category C
Map acceleration (g)	0.4	0.4
Soil Class	D (250 m/s<vs<350 m/s)	II (vs=400 m/s)
Response Modification Factor	6.5	5.5
Displacement Amplification Factor	4	5.5 or 1.0*
Fundamental period of building	0.2 sec	0.2 sec

*Not defined in the Chilean Code. Some designers use 5.5. Most designers use 1.0.

The study considered calculation variables as base assumptions for the seismic analysis. Both codes assigned similar values for most of these variables. However, some differences can be noticed concerning the values assigned for the Response Modification Factors and the Displacement Amplification factor (Table 6). These differences resulted in significant variations on base shear calculations and inter-storey drift restrictions that affected the final result of the seismic design.

a) Base Shear and the Response Modification Factor

Both design codes defines the base shear of the building as the product of the seismic coefficient by the total weight of the structure. The Seismic Response Factor determines the allowable relative acceleration of the structure in the base shear equation. This factor is based upon post-earthquake evaluations and currently is not based on rational analysis. Two main differences can be noticed between both codes:

- A building designed in Chile will be required to resist 16% of the building weight acting in a lateral direction, while the same building designed in the United States would be required to resist 6.2% of its weight. As a consequence, the Chilean code require its buildings to be 2.6 times as strong as the code of the United States expect its buildings to be.
- Both design codes require that an accidental torsional load should be superimposed upon the lateral design of the structural system and demand that the walls of the building be even stronger. The U.S. requirement assumes that the torsional effects of all stories have an equal effect on the overall response but the effect is only one-half that expected in Chile.

Together these two requirements effectively result in Chilean buildings to be designed to resist forces on the order of 3.0 times higher than the same building designed in the United States.

b) Chilean Drift Restriction and the Displacement Amplification Factor

The second check for an anti-seismic structure is a drift check. The drift is defined as the difference in the deflections of two adjacent stories divided by the story height. In Chile, buildings are required to not deform more than 0.002h measured at the center of mass, h is the story height. This value was defined based on the experience on reinforced concrete seismic design, while in the U.S., the requirement for wood is 0.025 h.

According to the Chilean code, a building with 2.4 m high walls has an allowable inter-storey drift of 0.9 mm if the Displacement Amplification Factor is considered as 5.5. This value does not consider the proper flexibility and energy dissipation of timber structures. However, the allowable drift is 4.8 mm if the Displacement Amplification Factor is considered as 1.0. In this case the behavior of timber elements is closer to the shear capacity of the wall and a proper elastic response of the structure. Nevertheless, the Chilean code requires that the timber buildings be over 10 times as stiff as in the U.S.

Inter-storey drifts of both Midply and CLT systems applied to mid-rise structures have been tested with full-scale prototypes on shake tables. Results for Midply structures reported that the peak global drift at roof level was 166 mm and inter-storey drifts were approximately 1.3% (Figure 42) (Pryor et al., 2010). Meanwhile, results of the performance of the CLT prototype reported that the maximum inter-storey drift and maximum lateral deformation of the CLT buildings were 2.4% (X-axis) and 1.6% (Y-axis) (Figure 43) (Ceccotti, 2011).

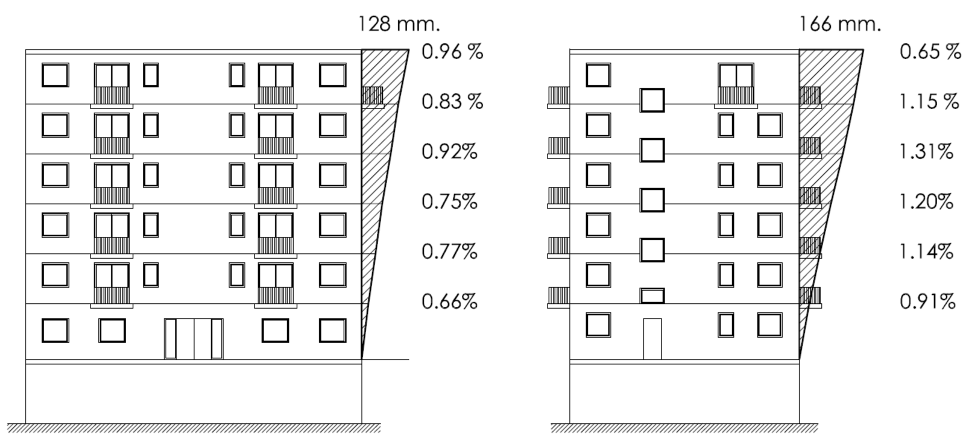


Figure 42: Midply building full-scale testing prototype. Inter-storey drift (%) and peak global drift (mm). Source: (Pryor et al., 2010).

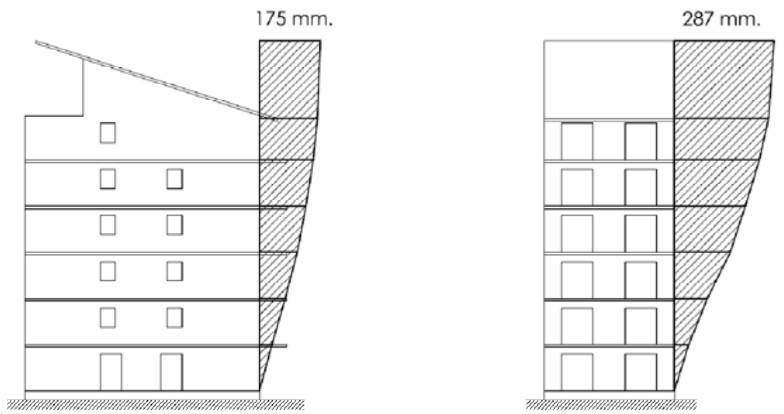


Figure 43: CLT building full-scale testing prototype. Maximum horizontal drift (mm). Source: (Ceccotti, 2011).

Both cases did not exceed the acceptable range (2.5%) of US Codes but are not capable to meet Chilean structural codes requirements for mid-rise structures. If timber structures are intended to be used in Chile, the drift allowance needs to be either relaxed for elastic drift checks or a drift amplification factor needs to be introduced with an associated inelastic drift allowance. Also the relative R-factors for timber need to be rationalized in a manner similar to the current effort in the United States.

As noted before, structural research on timber systems applied to mid-rise buildings are mainly conducted by universities initiatives in Chile. The University of Concepcion and Catholic University have shown an incipient interest in analyzing and validating these systems in mid-rise structures. The proposal of the University of Concepcion to analyze the behavior of timber shearwalls in mid-rise buildings aims to set the bases for seismic design of platform frame structures.

Modifications to the Chilean Structural Code will be proposed transferring experiences from the U.S. Further analytical research will rationalize the parameters for seismic design of shearwall structures in Chile. However, it is important to note that the scope and results of this research are limited only to platform-frame timber buildings (Giuliano Morbelli).

Engineers from the Catholic University of Chile studied the feasibility of a 5-storey timber building in the Chilean context. The design considered the first storey in reinforced concrete and the 4 upper storeys in platform-frame system (Figure 44). For design purposes, gaps of the Chilean Structural and Building

Codes regarding design and technical issues were adjusted using considerations from the International Building Code (IBC)[9]. Preliminary results are consistent with the need of a timber-oriented code according to the Chilean context. The research recommends that code restrictions must properly fit the structural behavior of timber-structured buildings, but also recommends significant changes regarding the certification of building materials, fire safety and seismic codes as discussed above.

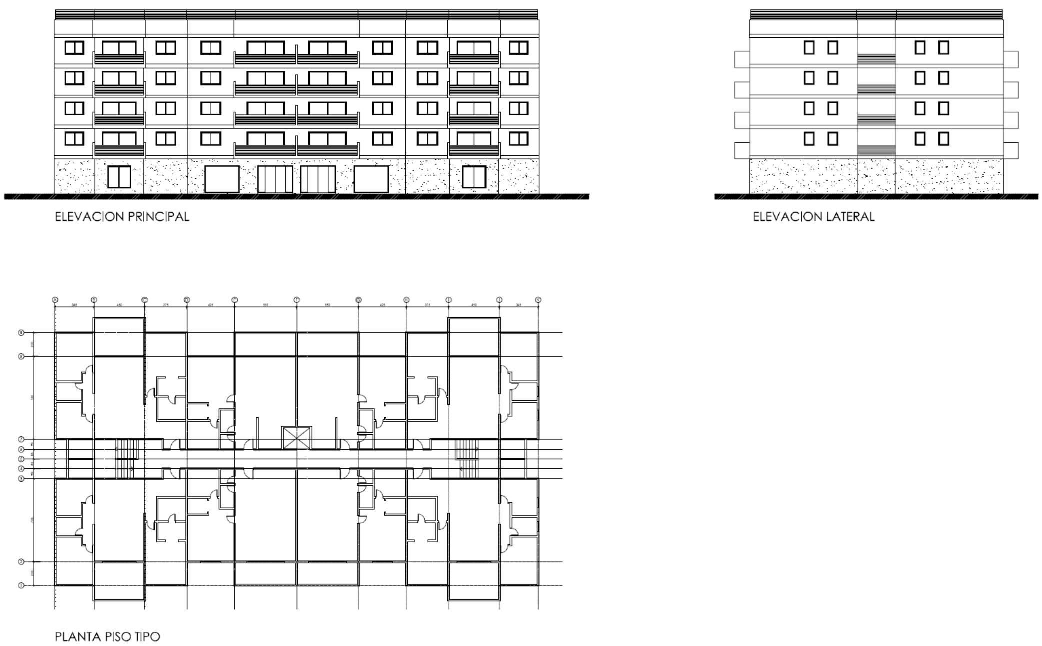


Figure 44: Platform-frame 5-storey building used for seismic analysis according to the Chilean context.

Considering the enhanced performance of massive panels under seismic loads, this research proposes the feasibility of a housing building using CLT panels. The same building layout was considered and all calculations were made according to Chilean Structural Codes. The final design considered 266 mm thick CLT panels and oversized steel connectors to meet the inter-storey drift requirements (see Appendix). These results verify that the design meets the current structural standards but dimensions of the elements signify an additional cost affecting the feasibility of the project (Figure 45).

[9] The Chilean Building Code does not require a second independent exit route or sprinkler system and smoke detectors.

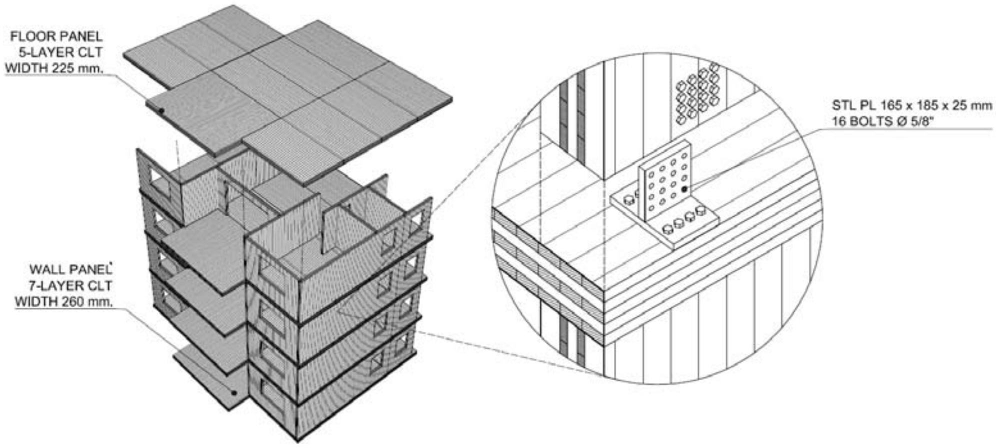


Figure 45: Right: design of a 5-storey CLT building according to Chilean Structural Codes. Left: Detail of the connectors to meet the inter-storey drift requirements.

4.5.2 The Chilean Building Code (OGUC)

In Chile, the environmental performance and fire safety of all buildings is regulated by the Chilean Building Code (Ordenanza General de Urbanismo y Construcciones (O.G.U.C)). Besides structural considerations, design of walls, floors and roof components must meet the code requirements. This research compares the Chilean Building Code standards with the Canadian standards as a reference with an important tradition in timber buildings. Also recommendations from the major manufacturers of timber components in the Northern Hemisphere are considered as design guidance.

Environmental performance

The environmental performance of a building is mainly conditioned by its envelope. Construction details must ensure proper heat, air and moisture control. Local construction techniques are reflected in the manufacturing of the enclosure, so it is possible to identify different construction details according to different local construction standards. Main variations in wall details between regions consist in the implementation of the vapor barrier, moisture barrier; and on the location and thickness of the insulation.

The development of efficient solutions with less layers of building materials can significantly impact the cost and performance of the building. Less on-site work allows for greater accuracy of prefabricated elements. Special considerations are required during construction process to ensure the proper seal and performance of the envelope.

Normally an enclosure element is composed of an exterior finish that controls rainwater, an insulation layer, structure and an interior finish:

a) Exterior Finishes: Rainwater Control and the Weather Resistant Barrier (WBR)

Wood panels are moisture sensitive structures and must be protected from rain and other moisture sources through properly assembled finishes. Rainwater can affect the long-term performance of timber panels. The best practice strategy for rainwater penetration control is a drained and ventilated rainscreen cladding (Finch et al., 2011).

The structural-independent exterior finish allows for a wide variety of alternatives. Apart from timber façades, slab and metal façades are also possible. In North America and Europe, many timber building are finished with bricks cladding. As a result, the structure is not apparent from the outside. CLT is not considered as a cladding material because it is not design to be exposed to weather conditions. Also, according to BCBC exterior cladding materials must be noncombustible; protected by a thermal barrier and wall assembly or be fire retardant treated wood tested for fire exposure. The cumulative effect of rainfall in mid-rise buildings must be considered for exterior cladding. The proper seal of the façade is particularly relevant for timber structures that must be kept dry at all times.

The tighter the material of the outer shell, the more important is the installation of a back-ventilation layer or tight vapor retarder or barrier. Breather type sheathing membranes (such as Tyvek Commercial Wrap) are commonly used in permeable air barriers. However, CLT panels behave different from conventional wood-frame structures due to the characteristics of massive timber panels. CLT panels absorb a large amount of moisture when exposed to humidity, and drying may be slow due to massive wood.

Moisture content must be adapted to the intended service conditions. If the moisture content of the timber is far from the relative humidity in the intended environment forces may break the joints and deformations may also follow. Weather resistant barriers (WBR) are installed in the exterior side of panels to keep them dry.

Today there is no consensus about the specifications of weather resistant barriers in massive timber systems. PFInnovations (Finch et al., 2011) recommends the use of high vapor permeance barriers (i.e. house wrap or comparable products) combined with rigid insulation boards. While KLH (2011) suggests a convection barrier or vapor retarder depending on the type of insulation and facade structure used. Both FPInnovations and KLH locate the WBR on the exterior face of the CLT panel, while projects developed by Nordic Engineered Wood (Oberholzer, 2012) considered WBR on the exterior face of the insulation. Finch (2011) notes that risk increases when impermeable materials are used as barriers because panels may not dry out when initially wetted. Therefore it is not recommended to place vapor retarders on both sides of massive timber panels.

b) Insulation

Construction details define the thermal transmittance (U-value) of the enclosure. The U-value is the rate of transfer of heat per area and difference of temperature across the structure. It can also be noted as the reciprocal of the thermal resistance (R-value). A well insulated enclosure will have a high thermal resistance. The R-value mainly depends on the conductivity and thickness of the building materials used in the envelope. To calculate the R-value of a multi-layered section, R-values of the individual layers are added. R-value is expressed in either US units ($h \cdot ft^2 \cdot °F/Btu$) or the International System of Units ($K \cdot m^2/W$) where the abbreviation "RSI" is used.

The Chilean Building Code defines the thermal performance according to the geographic location of a building. The design proposal of this research is located in the city of Santiago (Zone 4) that has a Mediterranean climate. The Chilean Code requires an insulation of R-3.4 (RSI 0.59 K·m²/W) for Santiago, while in most Canadian jurisdictions a nominal insulation in the range of R-20 (RSI 3.52 K·m²/W) is required in walls (Finch et al., 2011). Thermal requirements for buildings in Santiago are significantly less demanding than Canadian Standards. Furthermore, the Chilean Code considers Zone 7 as the most demanding zone the country with a climate similar to the one in British Columbia. As shown in Table 7, even thermal requirements for Zone 7 do not meet Canadian standards.

Table 7: Thermal requirements for housing by the Chilean Building Code and BCBC.

	Chilean Building Code				BCBC	
	Zone 4 (Santiago)		Zone 7			
	R	RSI	R	RSI	R	RSI
Exterior Walls	3.4	0.59	9.5	1.67	20.0	3.5
Suspended Floors	9.5	1.67	17.8	3.13	27.8	4.9
Roof Joist Assemblies	14.9	2.63	22.7	4	27.8	4.9

In a wood frame system insulation is applied within the panel. The maximum thickness of the insulation is defined by the thickness of the panel. In case of additional insulation, an auxiliary structure is necessary. For example, the required insulation for exterior walls according to the Canadian jurisdiction is achieved by insulation thickness from 5” to 6”. Wood frame system exterior walls are usually built using 2” x 6” studs not by structural requirements but to meet thermal requirements. The available thickness for insulation inside Midply walls is only 4”, so the system does not meet Canadian insulation requirements by itself. If Midply elements are intended to use in the enclosure of the building in Canada, an auxiliary structure is needed to install insulation on the exterior side of the wall.

In Chile, 2-inch thick thermal insulation (mineral wool) meets the requirements for wood frame walls in Santiago, while 4-inch insulation meets the performance for roof structures, so no additional structure is required according to thermal insulation requirements.

In the case of massive timber panels, the low conductivity of wood provides a high thermal resistance. Softwood species which typically make up CLT panels, provide a RSI value of approximately R-1.2 (RSI 0.21 K·m²/W) per inch. Insulation on the exterior side of the panel is recommended to protect the wood. Rigid insulations are recommended as they can be fastened to the structure. However, insulation must be vapor permeable to avoid trapping moisture and damaging the wood. Insulations such as rigid mineral fibre or wood fibre insulation boards are recommended by FPInnovations. Extruded polystyrene and expanded polystyrene are suitable but not recommended because their vapor permeability is relatively low.

Table 8 shows the required additional insulation for CLT panels according to Canadian Standards. For 3-layered wall panels, only 4 inches of additional insulation (RSI 4/inch) are required to meet Canadian standards (R-20). In the case of Chile, most 3-layered CLT panels meet the thermal requirements for Santiago with no additional insulation due to the low thermal transmittance of wood. This feature can result in significant construction savings compared to other traditional systems. Masonry and reinforced concrete walls commonly require 1-inch insulation to meet the thermal requirements of Zone 4.

Table 8: Building enclosure design for CLT panels Source: (Finch et al., 2011).

Required Nominal Insulation R-value (RSI)	CLT thickness Inch (mm)	CLT Insulation R-value (RSI)	Additional Insulation Thickness Inch (mm) R=4/inch
20 (3.52)	2.0 (50)	2.4 (0.42)	4.5 (114)
	3.5 (89)	4.2 (0.74)	4 (102)
	5.5 (140	6.6 (1.16)	3.5 (89)

c) Vapor Barrier and Interior Finishes

The purpose of vapor control within a wall, ceiling and floor assemblies of a building is to limit the flow of moisture by vapor diffusion from the inside, thereby preventing interstitial condensation.

For wood frame systems, suitable design solutions consider a sheet of asphalt impregnated kraft paper (vapor retarder), polyethylene (vapor barrier) or, in some cases, vapor retarding paint on the gypsum board. Designs must considerate avoiding situations where water may become trapped within the wall by incorrect placement of the vapor barrier (Finch et al., 2011). In a wood frame system, vapor control is located on the inside surface of the panel.

Massive timber panels have a low vapor permeability that provides an additional air barrier. The vapor permeance of a 3 1/2 inches softwood CLT panel controls the vapor flow in most situations. CLT panels themselves may meet the requirements for both vapor retarder and vapor barrier (Finch et al., 2011).

Also panels can be exposed from the inside if fire requirements are met. For example, in the Svartlamoen Housing Building, exposed panels were used as interior finishes. Timber creates a rough interior where furnishing and equipment can be directly bolted to the walls (Figure 46). However, designs must consider exposed electrical wiring.

Figure 46: Svartlamoen Housing Building (Brendeland and Kristoffersen architects, Norway, 2005). Left© (Grandorge, n.d.) Center, Right © (Fowelin, n.d.) Used by permission.

Usually in timber structures gypsum boards are used in interiors not only as an aesthetic finish, but also to meet fire safety requirements as is detailed in the next chapter. Special considerations should be taken with interior finishes in bathroom and kitchens. A common practice is to leave finishes is to leave a 2-inch gap in services areas to install the utilities.

d) Fire Performance

Wood is a combustible building material. However, the combustibility or non combustibility of a building material does not fully define the fire resistance of building elements. Timber components are usually built from layers of different materials. Fire resistance is a property of the component that designates a minimum period of time for the element to remain functional when exposed to a fire. Is designated as “F-X” or “FRR-X” where “X” are the number of minutes an element must meet both loadbearing functions and separating functions to prevent the transmition of smoke and heat.

Well-designed timber components satisfy fire requirements through the encapsulation method or the charring method.

The encapsulation method is the correct combination of building component layers to meet the code requirements such as load bearing walls covered with plasterboards and filled with an insulating material. Additional covering can achieve higher resistance for elements like party-walls. In wood frame construction fire can spread through the cavities left by an assembly. In these cases all cavities must be encapsulated and filled with insulating material.

The charring method considers that exposed loadbearing timber components can achieve fire requirements through larger cross-sections because the burnt layer of charcoal produces a natural layer of insulation. The charring rate of timber is used to design the section with additional layers as sacrificial layers with no structural function. Outermost charred layers build-up a heat protective zone that protects underlying layers of the element.

Midply walls use the encapsulation method to achieve the proper fire performance of the panels while CLT panels consider the charring method, encapsulation method or a combination of both as fire protection alternatives.

For Midply panels double walls, layers of gypsum boards and fire insulation are commonly used to reach FRR-60 and FRR-90 according to code requirements. In the case of the encapsulation method applied to

CLT panels, gypsum boards with fire protection are commonly used to improve fire performance. It can be assumed that a 15,9 mm thick board has a resistance of FRR 30 (Craft, 2011).

In the case of the charring method applied to massive timber panels, KLH considers the timber charring rate of 0.67 mm/min for top layers and 0.76 mm/min the other layers (KLH, 2008), while FP Innovations considers 0.65 mm/min. ((Craft, 2011)) and Leno, 0.7 mm/min ((Finnforest, 2011)). This means that for a 5-layered element there is a possibility for at least one layer to be burned away in the case of 30 min fire exposure (Figure 47). In comparison with structural timber and Glulam, the charring rate is higher due to possible gaps between the boards that make up layers.

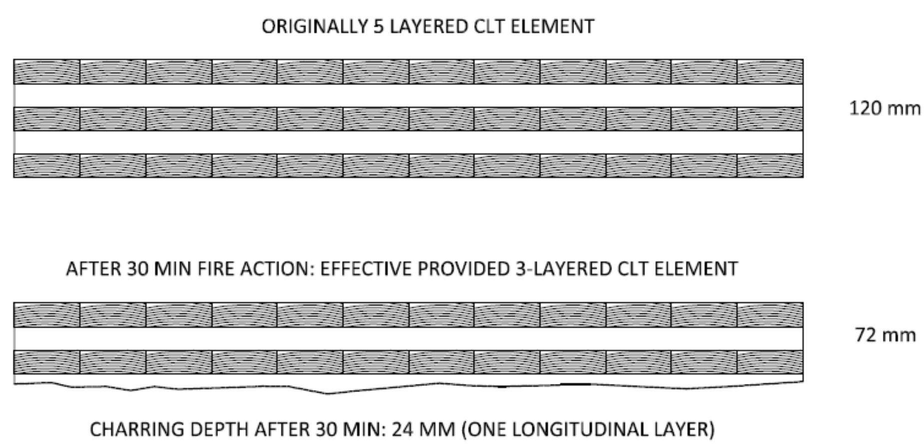


Figure 47: Loss of stiffness of a one-sided, fire exposed CLT-element. Source: (Augustin, 2008).

Certified solutions by manufacturers and research organizations combine these two methods to provide design alternatives. Various possibilities can be used to meet the required standards for mid-rise buildings (Table **9**). Despite the fact that 3-layered wall panels usually meet structural requirements for mid-rise buildings, 5-layered panels provide the fire resistance (FRR 60) required by the Canadian code. KLH proposed alternatives consider thinner panels and less encapsulation than other manufacturers and organizations.

Table 9: Certified fire resistance of CLT panels. Sources: (Craft, 2011; Finnforest, 2011; KLH, 2011).

Wall Panels

FRR	CLT Thickness (mm.)	No of Layers	Gypsum Board Fire Protection Thickness (mm.)	Source
30	>60	3	-	KLH
	85	5	12.5	Leno
	115	5	9.5	Leno
45	114	3	15.9	FPInnovations
60	>117	5	-	KLH
	85	5	20	Leno
	115	5	15	Leno
	120	5	-	Leonardo DaVinci Pilot Project
	140	-	-	BCBC
90	85	5	15+15	Leno
	94	3	18+18	KLH
	95	5	15	KLH
	115	5	15+15	Leno
120	95	5	15+15	KLH

Floor Panels

FRR	CLT Thickness (mm.)	No of Layers	Source
90	146	5	KLH
	190	5	FP Innovations

The Chilean Code stipulates the fire resistance according to the function of the elements and the height of the buildings. Unlike Canadian standards, the Chilean Building Code does not consider specific requirements for combustible and non-combustible structures. Therefore, it does not require the use of sprinklers systems for timber structures. Chilean code requirements fit to the performance of reinforced concrete as it is commonly used in mid-rise buildings. Thus, fire resistance performance according to the Chilean Code is more restrictive than according to the Canadian code, but less specific concerning timber systems (Table 10).

Table 10: Fire-resistant rating required for housing according to the Chilean Building Code and BCBC.

	Chilean Building Code			BCBC
	< 4 Storeys	5 Storeys	>6 Storeys	< 6 Storeys (sprinklered building)
Firewall	120	150	180	60
Staircase	90	120	120	60
Structural Wall Wall Between Units Elevator Shaft	60	90	120	60
Partitions	-	15	30	-
Floor Slab	60	90	120	60
Roof Slab	30	60	60	60

One alternative to define the fire resistance of structures is using the certified fire resistance of construction materials according to the Chilean Building Code. In this case the code assigns standard acceptable Fire Resistance (F values) for traditional building materials according to the width of the element[10]. Table 11 compares assigned values for timber and concrete as the most common used building materials for mid-rise buildings in Chile. Considering this methodology, 3-layered CLT panels (or 90 mm width) can be assigned F-60 while 5-layerd panels (or 140 mm width) can be assigned F-90. This performance meets the structural walls requirements for 4 storey residential buildings according to the Chilean Code. For other elements such as staircases or higher structures, gypsum boards can be used to encapsulate timber elements and panels to enhance their fire performance.

Table 11: Certified fire-resistance rating of timber elements according to the Chilean Building Code.

Material Width (mm.)	F15	F30	F60	F90	F120	F150	F180
Timber Column	45	90	160	-	-	-	-
Massive Timber Panel	20	45	90	140	190	-	-
Concrete	-	-	-	100	-	150	200
Gypsum Board	12.5*						

* F-15 to F-120 boards are available subject to suppliers' availability.

[10] Also, solutions tested by the American Society for Testing and Materials (ASTM), Underwriter Laboratories (UL) or Deutscher Normenausschuss (DIN) are accepted by the Chilean Building Code.

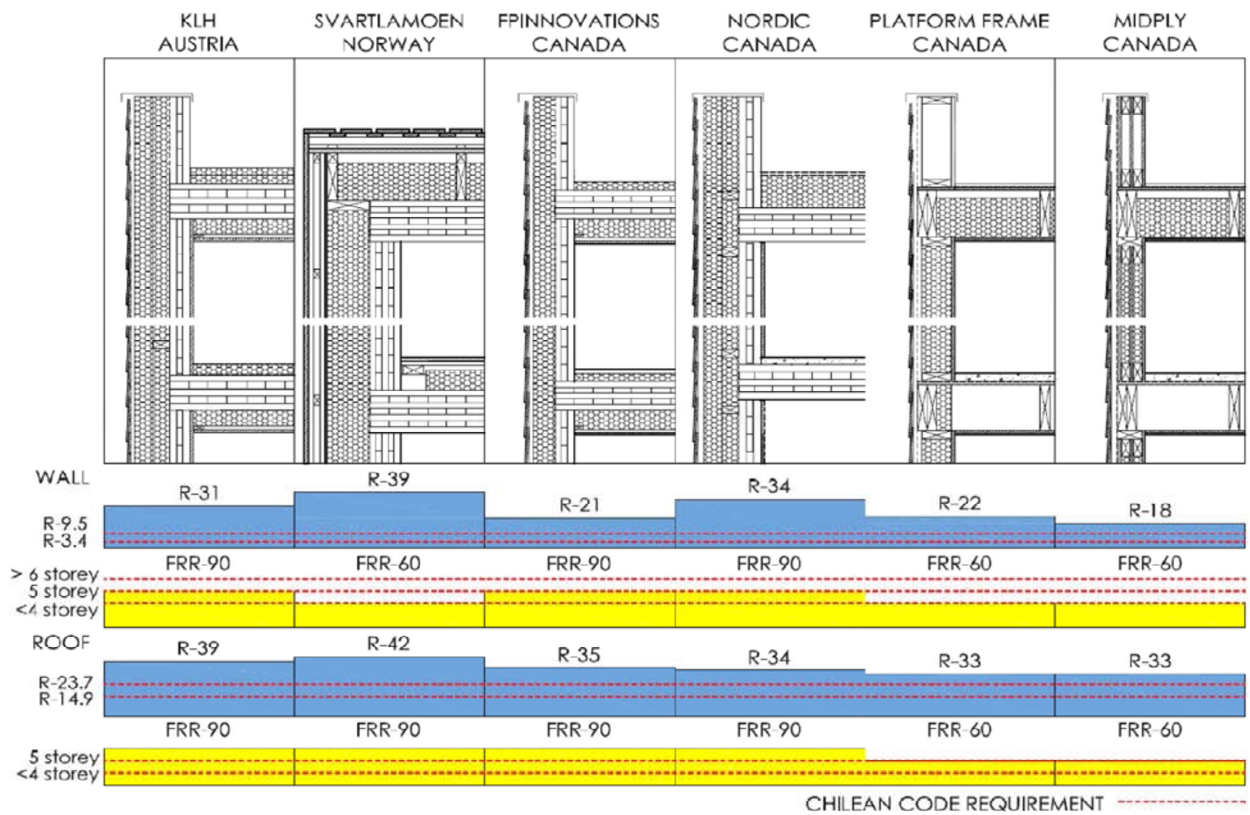
Considering local codes and standards, the Chilean Fire Safety considerations are similar to the Canadian Standards, while thermal performance requirements are significantly less demanding. To evaluate the performance of different solutions according to the Chilean standards, a comparison between detailed sections of various building systems is shown in Table 12. The systems considered are standard wood frame, Midply wall, CLT recommended by KLH, FPInnovations and developed by Nordic and been detailed following technical assistance by manufacturers or constructive details of built cases.

Construction details show different arrange of components and thicknesses of building materials that result in diverse thermal resistances and fire performances. The main difference between traditional wood frame and massive timber systems is the application and location of insulation in building walls. CLT panels are an interesting alternative as insulation is attached on the exterior face of panels and does not depend on structural considerations.

All the studied roof assemblies meet the thermal and fire requirements for residential buildings according to Chilean codes. Also, all walls assemblies meet the thermal requirements for all regions in the country and fire resistance standards up to 4-storey structures. In cases of higher structures, additional fire resistance can be achieved through the installation of gypsum boards in the interior of wall panels.

In summary, specifications suggested by manufacturers and organizations related to the timber systems in the Northern hemisphere meet the thermal and fire codes requirements in Chile.

Table 12: Comparison between detailed sections and enclosure performance of CLT, Midply and Wood Frame building systems. Sources: (Finch et al., 2011; Karacabeyli & Popovski, 2010; KLH, 2011; Oberholzer, 2012; *Total housing*, 2010).



Exterior Wall	3-layer CLT 94 mm	5-layer CLT 144 mm	3-layer CLT 89 mm	3-layer CLT 114 mm.		
Specs	Back Ventilated Facade Wind Proofing 2 x 80 mm. Rock Wool w Wooden Elements Convection Barrier CLT panel w/Connect Sealing Level 15 mm Gipsum Board	Facade 22 x 73 mm Wood 36 x 48 mm Wood 23 x 36 mm Wood 9 mm Gypsum Wind Breaker 48 x 198 mm wood, mineral wool CLT panel	Facade 1" Vertical Wood Straping 4" (102 mm) Insulation R-4/Inch Vapor Permeable WRB CLT panel w/Connect Sealing Level	Facade 1" Vertical Wood Straping 2x 3 1/2" Mineral Wool Vapor Permeable WRB CLT panel w/Connect Sealing Level 15 mm Type 'X' Gipsum Board	Facade 3/4" Treated Plywood 2 Layers 30 Min Building Paper 38x140 mm (2"x6") Studs w/R-20 Glass Fiber Batt Insulation 0.15 mm. (6 mil) Poly Vapor Barrier 15 mm Type 'X' Gipsum Board	Facade 3/4" Treated Plywood 2 Layers 30 Min Building Paper 2 x 38x140 mm. (2"x6") Studs w/ Glass Fiber Batt Insulation 12.7 mm. (1/2") OSB 0.15 mm. (6 mil) Poly Vapor Barrier 15 mm Type 'X' Gipsum Board
Roof Slab	5-layer CLT 182 mm	7-layer CLT 208 mm	5-layer CLT 146 mm	5-layer CLT 175 mm		
Specs	Roof Membrane 80 mm Heraklith DDP Vapor Barrier CLT panel 80 mm Mineral Wool 15 mm Plasterboard	Facade 36 mm Battens Water Proof Memb. 23 mm Battens 21 mm Plywood 48 mm Air Gap 48 X 198 mm wood, mineral wool CLT panel	Roof Membrane 80 mm Heraklith DDP Vapor Barrier CLT panel 80 mm Mineral Wool 15 mm Plasterboard	Waterproof membrane 160 mm Mineral Wool CLT panel	Waterproof membrane 21 mm Plywood I-joist w/200 mm Mineral Wool Vapor Barrier 15 mm Gypsum Board	Waterproof membrane 21 mm Plywood I-joist w/200 mm Mineral Wool Vapor Barrier 15 mm Gypsum Board

4.6 Discussion

The suitability of using Midply and CLT systems to the Chilean context is based on the analysis on resource availability, manufacturing feasibility, market feasibility, structural performance and local building codes.

Resource Availability

Chile has abundant forestry resources but softwoods are the main products. Radiata pine timber has low resistance to compression stresses perpendicular to the grain; this condition represents a difficulty in the performance of panels located in lower storeys of mid-rise buildings. However, Radiata pine as a softwood is suitable for massive timber elements as CLT panels systems have low bending stresses[11] (Chapman, 2011). Thus, further research is needed to explore the application of softwoods in timber panels.

Manufacturing Feasibility:

In Chile, the application of prefabricated systems in construction processes could improve the quality of manufacturing and lower construction costs. However, prefabricated panels should be adjusted to the local manufacturing possibilities.

Wood frame and Midply systems can be considered as low-cost systems compared to massive timber. The production development requires little initial investment as the system uses the same components from traditional timber techniques. Midply panel manufacturing uses less wood than massive timber. However, to develop mid-rise buildings it is required the availability of timber elements with improved standards. For example, 2"x10" lumber is commonly used in floor panels in North America, but its availability in the Chilean market is limited so design of panels is limited by 2"x 8" elements. Also, in the case of CLT panels Chilean nominal 2” x 4” studs are actual 42 mm x 90 mm. CLT manufacturing using

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[11] CLT panels systems have low maximum bending stresses of around 5 N/mm^2.

these studs result in 135 mm thickness (3-layer) and 210 mm thick (5-layer) panels that differ from the panel thickness used Europe and North America.

Market Feasibility:

According to market researches, users had strongly ingrained prejudices against the use of timber in buildings. Wood was considered a low-quality construction system and is commonly associated with fire hazards and pests. CLT systems could fit better to the expectations of users as it massiveness shows similarities with Chilean traditional systems like adobe or reinforced concrete.

Structural Performance

For purposes of architectural design applied to structural calculations, rules of thumb can be easily applied to define an approximate dimensioning of the elements. Tables and considerations from manufacturers are helpful to get an approximate idea of sizing of wall and floor panels. However, in a later stage a through static analysis is necessary.

Midply systems consider the standard platform frame structure as base for structural design, environmental and fire performance. The use of platform frame standards and materials allow an easy adaptation of manufacturing processes to Midply elements. Also, the flexibility of manufacturing allows an easy integration of these new structures into existing buildings and to other structural systems such as post and beam or massive timber.

The main restriction for Midply walls is the required vertical continuity of the element down to the base of the building. This condition ensures the enhanced performance of shear walls to lateral loads.

In the case of CLT panels, the structural behavior of massive timber systems is closer to concrete than to wood post and beam structures. For walls, it is safe to consider 3-layered panels[12] for the upper three storeys, while 5-layered panels are a reasonable approximation for lower storeys. Design of connectors requires special considerations as they are weak points of the structure due to seismic loads.

[12] Thickness of 114 mm. using 38 mm. thick layers according North American manufacture standards.

In the case of slabs, it is important to note that design restrictions are defined by serviceability considerations. The maximum vibration and maximum deflection allowed usually define the thickness of a slab panel. For preliminary design purposes, span to depth ratio of floor panels can be defined 1/20 to 1/30 according to Malczyk (2011) or 1/28 to 1/32 according to Gagnon (2011). According to these guidelines, floor panels from 150 mm to 250 mm in thickness meet the requirements for 5 meters spans. In other words, a preliminary design that considers 5-layered[13] CLT floor panels is a good practice for residential buildings with maximum spans of 5 meters. Thinner panels usually do not meet structural requirements and 7-layered panels often are not feasible due to high-cost considerations.

Codes and Standards:

According to tests, both CLT and Midply systems have a structural performance suitable for countries located in active seismic areas. However, both systems do not meet the inter-storey drift requirements from the Chilean Structural Code. One alternative is to consider oversized massive timber structures and connectors to meet these requirements. However, it is not feasible due to the high costs associated. Modifications in the Code according to the flexibility and energy dissipation of timber structures are needed to encourage the development of Midply and CLT systems.

Environmental Performance

For Midply and CLT systems, differences can be noted in the recommended specifications between European and North American consultants and manufacturers. European manufacturers are oriented toward the implementation on the Passive House standard through the development of details that meet those thermal insulation requirements. American manufacturers are focused on the adaptation of wood frame techniques to these relatively new systems.

Usually CLT details have a better thermal performance than wood frame elements. Massive timber has a good thermal performance, and the insulation thickness is not restricted by the thickness of the wall

[13] Thickness of 190 mm. using 38 mm. thick layers according North American manufacture standards.

panel. However, the amount of wood used in the manufacture of Midply or platform frame panels approximately one third of the amount considered for massive CLT panels. This feature can be relevant in regions were timber resources are not as abundant as Eastern Europe and North America.

In summary, both Midply and CLT systems have suitable features for the Chilean context. However, further researches using local construction materials and techniques; and modifications in structural codes are required to encourage the development of these systems in Chile.

5. Architectural Applications of Panel Systems to the Chilean Context

Mid-rise buildings present a unique opportunity to apply new timber systems into innovative architectural interventions. Steel and concrete structures perform more efficiently in high-rise buildings than in mid-rise buildings. However, timber structures still have not been used in mid-rise housing buildings in Chile. They need to be improved to be a competitive alternative.

An architectural design project is an excellent opportunity to apply concepts and technical information to a real situation while providing additional information for the theoretical discussion. Within the various variables that the project considered in this proposal, only those relevant from the architecture's perspective of the project have been applied. Technical features of the system are considered more as an exploration of possibilities rather than as design constraints. The feasibility study incorporated technical aspects but also the social and cultural context of densification of Chilean cities as a unique case to use prefabricated timber systems.

The architectural project proposes a flexible solution to expand existing housing using the prefabricated timber construction system that fit the case of study. The choice of expanding housing buildings is based on their structure and modular spatial configuration that present following characteristics:

a) Apartment spans rarely exceed 5 meters (unlike the case of open floor plans in office buildings). These dimensions allow the design of floor structures using slab panels independent of structural beams.

b) Buildings designed by a repetition of the same plan layout are commonly structured with continuous walls through residential units. This structural scheme of rigid diaphragms has a seismic performance that exceeds that of post and beam structures.

5.1 Current Applications in Architecture

The application of new building materials and building systems into architectural projects sometimes is a slow and non-linear process. For example, when cast iron was introduced as a new building material in the 19^{th} century, its first applications in engineering projects replicated the construction logic of wooden structures. Only around 1850 the material developed its own building expression in the exploration of greenhouse structures culminating in Paxton's Crystal Palace. Later, through the introduction of steel as a new building material, steel frame buildings achieved their characteristic expression.

Similarly, development in new timber systems in the last 20 years is the result of the efforts of various organizations and companies interested in promoting the use of wood. Researches and studies have provided substantial technical information on these new systems to meet building and code standards. Although there is a growing interest from governmental organizations and private companies to promote application of new technologies in wood and its introduction into the market, its application in cutting-edge architectural projects is not clear. So far, most uses of new timber systems applied to mid-rise buildings have replicated the existing constructive logic of modernist buildings.

Architects and builders have been able to demonstrate the technical advantages of the material related to environmental and prefabrication benefits. However, most built projects have not yet explored in the spatial possibilities and new structural forms allowed by this technology. A clear example is the composition and finishes of the facades of mid-rise housing buildings that do not differentiate between reinforced concrete, steel or timber structures. Openings and outside finishes are not dependent on load bearing structure and do not relate directly to the materiality of the building. Currently, few cases that explore the spatial and structural potential of these systems are restricted to academic studies.

This analysis focuses on issues relevant for architectural design. Even when technical reports and manufacturers specifications are cited as technical references, only those aspects relevant to architectural design are considered. The objective of this architectural analysis is to provide tools for architects to design projects that explore and develop the features of these new timber systems. In this sense, general notions of structural design and technical solutions become fundamental to achieve these objectives. Comprehensive structural calculations and technical specifications are considered at a later stage of development of design.

In general terms, timber panel structures can be developed entirely in wood panels or combined with other structural systems (e.g. post and beam) or other building materials (e.g. reinforced concrete, steel).

Murray Grove by Waugh Thistleton Architects is a 9-storey platform framed structure entirely made out of CLT load bearing walls and roof slabs as well as stair and lift cores (Figure 48). The installation of prefabricated panels dramatically reduced construction periods. The assembly of the entire building was completed within 49 weeks. The building has an orthogonal plan layout with short spans, so it fits perfectly to a prefabricated panel system. However, flexibility in interior spaces or in the façade is not possible due to load bearing walls.

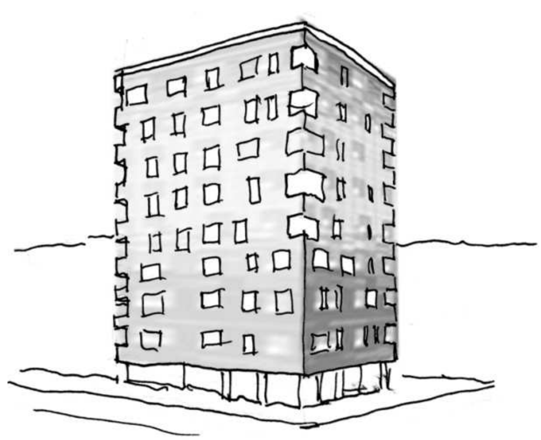

Figure 48: The Murray Grove Building (Waugh Thistleton Architects, 2009). All building's walls, floor slabs, stairs and elevator cores are made out of load bearing CLT panels.

To achieve greater flexibility in the design of the building, panel structures can be combined with other systems. The building E3 by Kaden Klingbeil Architekten, is a 7-story structure that combines a massive wood construction consisting of timber post and beams with infill solid wood walls. The frame provides a structural grid that can be freely filled with panels (Figure 49). The composition of the facade can be modified according to the apartment requirements.

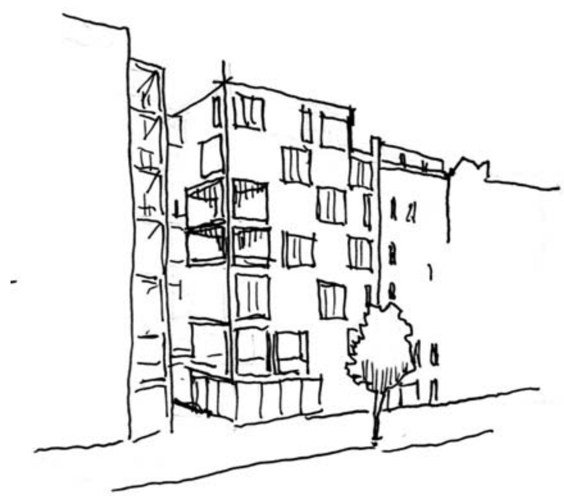

Figure 49: The Building E3. Center: Post and beams massive wood structure. Left: Solid wood panels as infill walls. (Kaden-Klingbeil Architekten, 2008)

Another alternative is the combination of timber panels with other building materials to achieve a higher structural performance. A design with a central reinforced concrete core allows a flexible arrangement of open plans. This configuration is commonly used in office buildings where the core hosts circulations and services while the open-plans areas are formed frame structure. The same concept can be found in Rundeskogen towers by Helen & Hard / dRMM Architects. The project consists of three towers of 12-15 stories with a total of 114 flats. The design has a central structural core and apartments that branch out at higher levels, leaving the ground plane relatively free. The organizing element of the entire project is the star-shaped reinforced concrete core and party walls. This concrete structure holds timber-modules that adapt to various apartment configurations (Figure 50).

Figure 50: The Rundeskogen towers. A central reinforced concrete core holds timber-modules (Helen & Hard / dRMM Architects, Norway, 2012). Image credit: dRMM Architects. Used by permission.

Structural configurations to achieve larger spans can be achieved through the development of folded structures or combining timber panels with steel or concrete elements.

In the case of the St-Loup Chapel by Hani Buri, Yves Weinand and Local Architecture the design was based on a research on Origami paper folding to develop folded plates structures (Buri & Weinand, 2008). Complex structures were analyzed and built using CLT panels milled by CNC machines (Figure 51). Performance is achieved by the geometry of the structure that expands the possibilities of prefabricated panels.

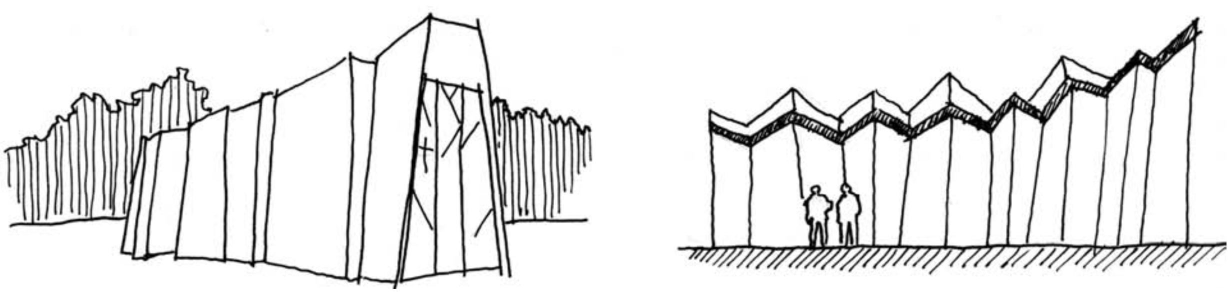

Figure 51: Chapelle de St-Loup. Right: General view. Left: Section. The roof geometry enhances the structural performances of flat panels. (Hani Buri, Yves Weinand, Local Architecture, 2008).

To achieve longer spans mainly in industrial buildings, gymnasiums or warehouses, timber plates are combined with pre-stressed steel systems. Wood is used as a material in compression, while steel rods hold tension stresses. This configuration allows the design of light long-span structures. A thesis by Falk (2005) explores this material configuration applied to tensegrity[14] systems (Figure 52).

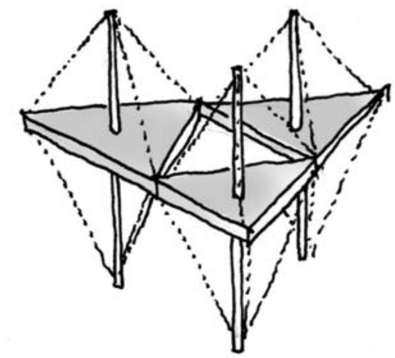

Figure 52: Study models of CLT panels combined with steel tensors applied to tensegrity structures (Andreas Falk, 2005).

Studies are not conclusive regarding experimental structures in massive timber. According to Schickhofer (2011) the cases of point-supported structures or cantilevered structures still require further research to evaluate their possibilities.

a) Architectural Expression of the Building System

Timber panel buildings are based on the arrangement of planar components. Thus volumetry must be conceived from planes that can be vertically, horizontally or diagonally orientated. If architecture design was conditioned by modular mass fabrication in the 20th century, today elements are fully customizable due to digital prefabrication. The use of standard components is no longer a restriction for architectural design. Building design now is able to express those repeatable elements or a design based in various different components.

The Naked House by dRMM Architects expresses in its design the possibilities of customized CNC manufacturing applied to massive timber panels. The design of this pavilion is decomposed into 2D

[14] Structural system developed by Kenneth Snelson of discontinuous compression struts with a network of elements in tension creating efficient and light structures.

component with unique perforations. Openings in panels constitute windows and doors; resulting parts obtained are reused as furniture or sculptural elements (Figure 53).

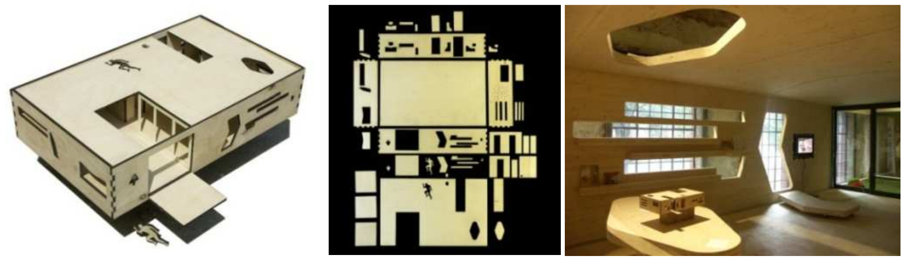

Figure 53: The Naked House. Center: CNC manufacturing is applied to customize each panel. Left: Resulting parts from openings are reused in the design. (dRMM Architects, 2006). Image credit: dRMM Architects. Used by permission.

Customized manufacturing also has benefits applied to mass processes. Traditionally, projects developed under mass production processes adjust the design according the dimensions of products available in the market. Projects developed under mass customization processes can develop various components according the specific requirements of the project at no extra cost. The Judenburg building by Mack Architects used new technology to develop wood timber construction of prefabricated panels and prefabricated laminated balconies (Figure 54). All 22 apartments express prefabrication concepts through the repetition of components and layouts, however the facade is articulated by the balconies' layout.

Figure 54: The Judenburg building. Mass customization of panels is used to manufacture modular components according the project requirements (MACK Architects, Frauengasse,2004).

Although planar elements are clearly recognized in both projects, the formal expression states two different principles. In other words, both projects are undoubtedly made from timber panels but one expresses the prefabrication of the product while the other expresses its customization.

Design possibilities that historically have been attributed to concrete structures now can be applied to timber structures. However, few built cases explore these possibilities in mid-rise structures. So far, most mid-rise housing buildings constructed using timber maintain a conventional expression and structural layout.

5.2 Architectural Design Proposal

Timber can also be used to add storeys to existing structures. Due to the lightness and stiffness of timber structures reinforcements can be reduced or avoided in many cases. In the case of CLT panels, the structure is lighter than concrete structures but spans are wider than lighter timber floors in general. This allows an adaptation to existing support modulation. Additions to existing building have been carried out in Umeå in northern Sweden where a hotel has been extended through the addition of storeys in light timber-frame and in a massive timber extension of a small hotel outside Vienna (Falk, 2005). Those examples share that the timber is not necessarily visible in the finished result.

The features of Midply walls make them an excellent alternative to renovate existing buildings. The studs and plates are the same as used in platform frame construction so no special elements are required. The customization of panels allows an easy adaptation to the existing structure. The addition of Midply walls can improve the seismic performance without any significant modifications in the layout or structure of the building.

The architectural design proposal addresses the application of massive timber systems related to the densification in the city of Santiago. This densification is achieved through the expansion of a social housing building commonly found in Chile. These buildings were extensively built from 1968 through 1978 and, today, they are located in urban areas that show a growth in population. The project proposes an overall design for this typology and complemented with specific construction details that could be applied in other projects as well.

The design proposal considers two different approaches to the case of study:

The first addressed the scale of the building related to its spatial configuration, urban context and climate considerations. The strategy is based on flexible structural and spatial configurations that allow for various layouts. The design defines a generic architectural configuration applicable to different cases. The proposal considers structural performance, local market conditions, social context and the construction status of the existing buildings.

The second approach applies detailed features of timber building systems to the case of study. Specific building details are designed to meet local building and structural codes. Also, the details consider local manufacturing timber industry processes, fire protection, thermal and acoustic standards. These generic designs can be used as reference for other projects as they are conceived as a small design handbook for the Chilean context.

5.2.1 Context: The Case of Densification of Cities in Chile

Since the 70s, Santiago has strongly developed its suburban area but during the past 10 years downtown districts have shown a growing-ratio considerably bigger than districts located at the periphery. Between 2002 and 2012 housing grew 87% in downtown Santiago (Labbe O., 2011). Today the growth is located primarily in the inner city resulting in densification (Figure 55).

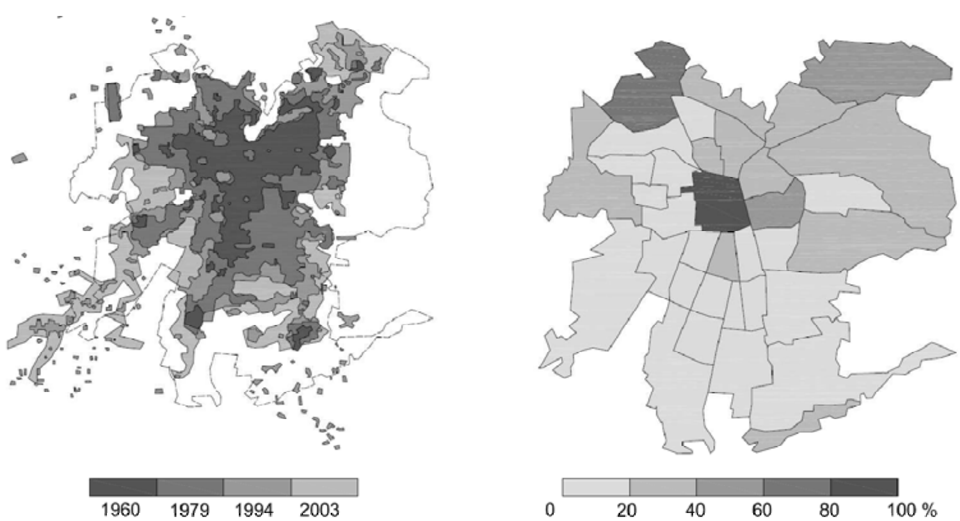

Figure 55: Left: Sprawl of the city of Santiago during the last 50 years. Right: housing percentual growth in Santiago during the last decade (2002-2012). Source: (Labbe O., 2011).

Today, developers are responding to this densification of the city in consolidated urban areas through mid-rise and high-rise housing. As these urban areas are already consolidated, the common development alternative is the demolition of existing structures to erect new higher and often denser buildings (Figure 56).

Figure 56: San Luis Housing, Santiago, Chile Source: (Briceño, 2012). Used by permission.

However, another alternative yet to be explored is the renovation or reuse of existing structures to increase density. A new addition to an old existing building can generate additional value for the residents but also for the neighborhood and reduce construction costs.

5.2.2 Case Study: Densification through the Expansion of Social Housing

In Chile, half of social housing developed during the past 20 years are mid-rise apartment buildings of 3 or 4-storeys (Rodríguez & Sugranyes, 2004). Despite design constraints and code regulations, expansion and renovation of apartments is a common practice in social housing. Risks of earthquakes, fire or fines do not stop the urgent need for more room. In buildings, 23% of owners expand their homes an average of 14 square meters. This is an important indicator of an owner's ability to improve housing (Rodríguez & Sugranyes, 2004).

Expansions are individual initiatives (Figure 57) but, in some cases, neighbors communities have agreed to perform coordinated expansions of buildings. The renovation and expansion of existing buildings are significant for urban planning as they avoid the expansion of the city in suburban areas.

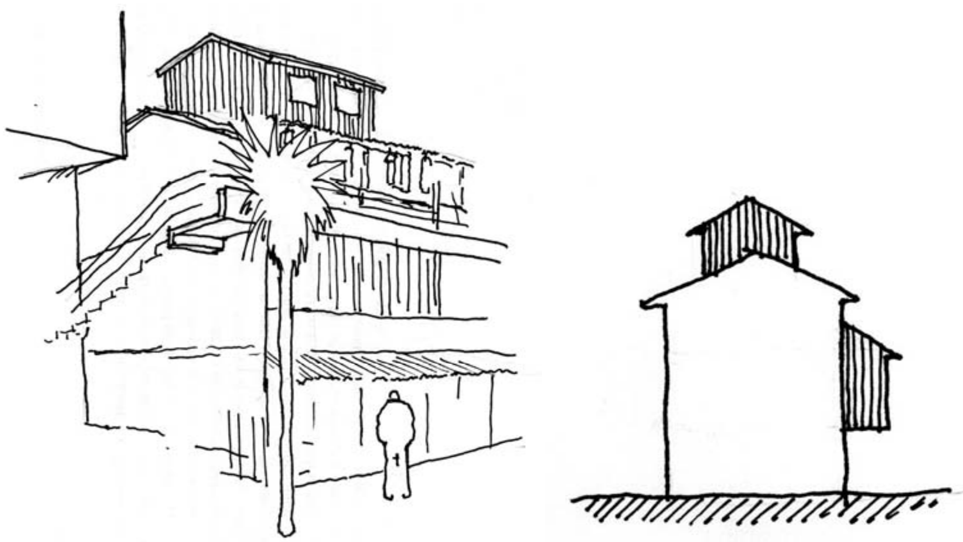

Figure 57: Owner-built expansions in mid-rise social housing. Source: (Curso Avanzado 2do Sem. 2008 Instituto de la Vivienda Facultad de Arquitectura y Urbanismo UNIVERSIDAD DE CHILE, 2007))

Los Quillayes Housing in the La Florida district of Santiago de Chile is an example of social housing coordinated expansion with institutional support from the City Hall, NGO and an architecture school (Figure 58). Fifteen apartments where expanded altogether setting a precedent for the improvement of living conditions in social housing (INVI, 2006). However, according to Rodriguez (2004), the model is still expensive and difficult to replicate on a large scale.

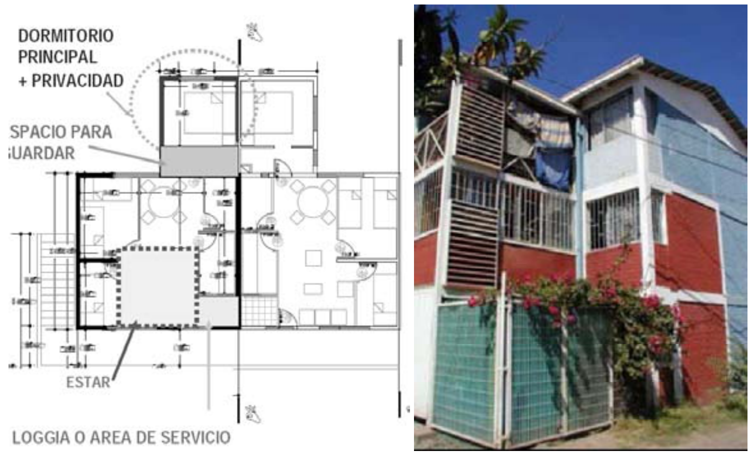

Figure 58: Los Quillayes Housing as a successful case of coordinated expansion of social housing. Source: (INVI, 2006). Used by permission.

The 1010-Buildings and 1020-Buildings

The 1010 and 1020 Buildings were developed between 1968 and 1978 and constitute a unique case of repeatable mid-rise social housing in Chile. In 1952, 30% of Chile's population lived in inadequate housing. The housing deficit came up to 323.616 units and 156.205 of them were located in urban areas. The Housing Corporation (CORVI) was created as an estate agent devoted to solve this housing shortage. This institution was strongly influenced by the modern movement; it approached the housing design as a "complete phenomenon" considering the stages of demand, budget, construction, urban and architectural design. Thus, housing projects were conceived of as rational solutions according to resources availability. Due to the high-cost of the projects assigned by architecture competitions, the corporation developed its own architecture studio for housing projects. In 1966 and 1967, the studio developed housing as a response for the victims of 1965 winter floods. The project was led by the architects Jaime Perelman and Orlando Sepulveda. It had the following features:

Urban Design: Influenced by the CIAM, the project proposed buildings as volumes isolated from their context located in open limitless spaces. The proposed grid did not match the existing city layout with blocks located next to arterial or structural roads. (Vigouroux Jaime, 2009).

Technological Considerations: Innovative industrialization and production processes were applied in the construction of the buildings. The modular design of the buildings was based on a dimensional coordination according to the construction materials used.

1010 and 1020 buildings consist of 4-storey buildings with 4 apartments on each storey. Apartments are two-bedroom (47 m^2) or three-bedroom (55 m^2) units. The volume is simple and abstract, creating a rational and repeatable module. Its structure is based on reinforced concrete walls located in the perimeter and party walls. The main facades are structured in reinforced concrete frames filled in with steel frames, steel windows and asbestos-cement window sills. All slabs (including the roof slab) are made of a 12 cm thick reinforced concrete structure (Figure 59). All interior partitions are not structural allowing eventual internal renovations. Facilities are conveniently located next to party walls serving all apartments. Facades are flat without any balconies or sunlight controlling elements.

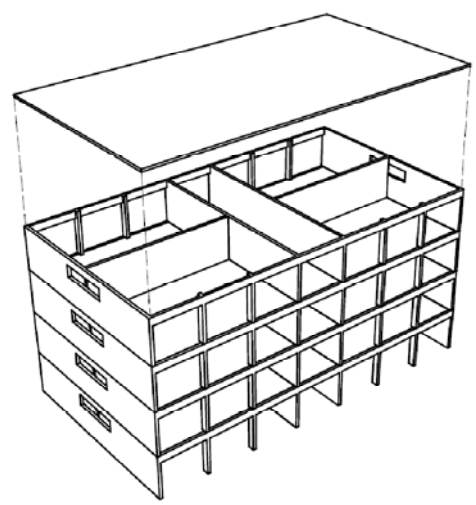

Figure 59: Structural layout of 1010 buildings based on reinforced concrete walls and slabs. Source: (Vigouroux Jaime, 2009)

Although these buildings were designed according to the climate of Santiago and once satisfied the flood-demands, developers promoted their development in other regions. CORVI accepted design changes depending on the climate zone, and the model was applied throughout the country. In desert climates from the north buildings considered flat roofs; in rainy regions of the south, buildings with tilted roofs and canopies over the access can be found. The model was so successful that "after about

10 years (1968-1978) and three governments 3,000 1010 and 1020 blocks were built throughout the country. At least 40,000 apartments were built and nearly 200,000 people live in this type of building (Figure 60)" (Vigouroux Jaime, 2009, p. 40).

Figure 60: Current situation of 1010 buildings in the city of Santiago.

Relevance of the Case Study

In Santiago, the model was applied to densify the suburbs in the early 70's. Usually they are located next to arterials all over the city. These areas have been already absorbed by the city's growth and now constitute consolidated neighborhoods (Figure 61).

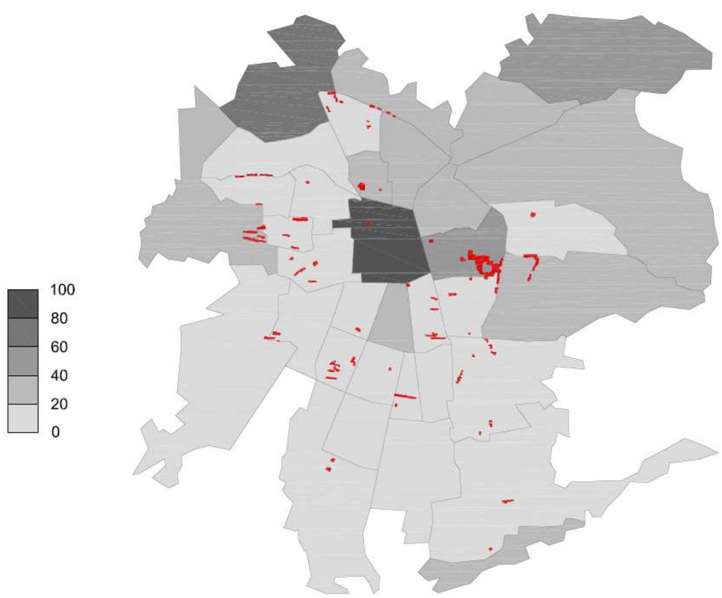

Figure 61: location of 1010 and 1020 buildings in the city of Santiago. Various of these buildings are in downtown areas with a significant housing percentual growth during the last decade. Sources: (Labbe O., 2011; Vigouroux Jaime, 2009).

However, the model has not changed or been modified since it was built. Thus, this housing model represents a unique opportunity for an expansion and renovation proposal of housing due to the following characteristics:

- It is a repeatable model that can be found all over the country with no variations on its configuration.
- Its reinforced concrete structure allows the addition of new structural elements. In particular, a structural roof slab allows a possible vertical expansion.
- Study cases have not had any significant alterations since they were built. It is feasible to propose an improvement of the spatial layout and environmental performance.

5.2.3 Precedents

The Porter House (2003) by Shop consists of a renovation of a six-storey warehouse to a residential condominium in New York City, USA. The original building from 1905 was expanded through a 4-storey structure. The exterior skin absorbs the floor height variations of the existing structure and the new addition. The volumes of the old and new parts of the building intersect to create a 2.4 m cantilever, and a gap that is converted into terraces.

Another case is the Falhle Building (2006) by Koko Architects in Tallinn, Estonia that consists of a renovation of an old warehouse from 1926. This 6-storey expansion with 68 apartments is rendered as a glass-sheathed volume. The first floor of the addition is set back from the existing structure creating a transition between both volumes (Figure 62).

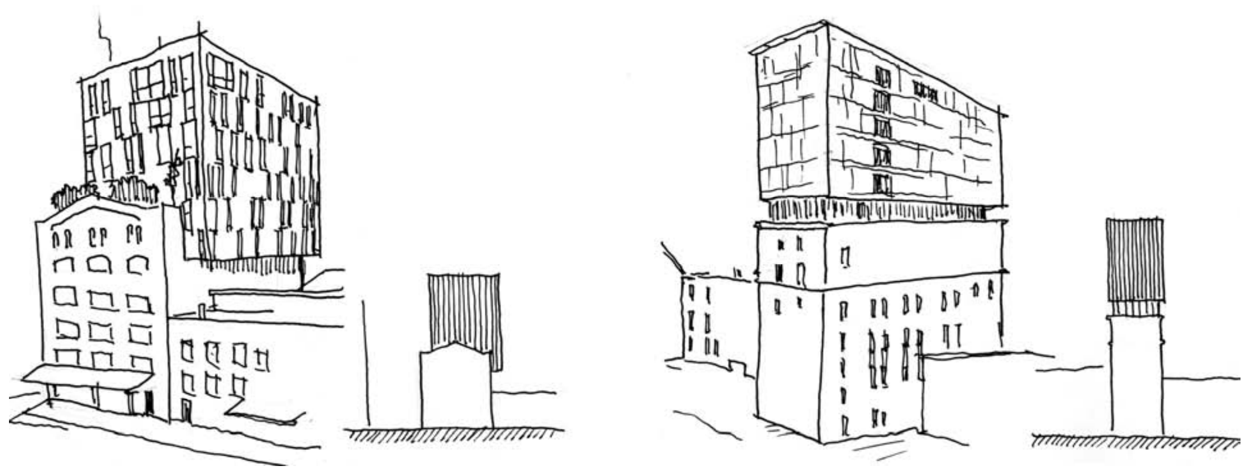

Figure 62: Two cases of vertical expansion and renovation of existing industrial buildings into housing using light-weight steel systems. Left: the Porter House (Shop Architects, USA, 2003). Right: the Falhle Building (Koko Architects, Stonia, 2006).

These cases are located in non-seismic zones and steel building systems perfectly fit the requirements of lightness and flexibility to expand reinforced concrete structures. This freedom allows open plans and flexibility in the façade composition.

Both additions in these examples contrast with the existing structures through their material and façade expression. However the relationships between new and existing buildings are different. At the Porter House the volumes clearly intersect while in the case of the Fahle Building both volumes are experienced as separate.

5.3 Proposal: Expansion of Reinforced Concrete Buildings in Timber Structures

The project proposes to expand 1010 buildings as a response to the densification of Santiago. Expansions should also enhance the existing structure and generate an additional value to the existing apartments. The proposal considers the expansion of these buildings using CLT or Midply building systems which features are:

- Prefabricated systems allow a quick mounting of the structure and minimize the impact to the residents and to the working site

- A light structure that does not require replicating the existing layout in the new storeys. This condition allows flexibility in design and the generation various apartment layouts. An expansion using reinforced concrete is not possible due to the high loads generated by the construction material.
- Special structural considerations should be taken for timber panels combined with concrete or masonry structures in mid-rise buildings. Lower concrete and upper timber systems can be considered as two separates structures if the stiffness of the concrete structure is 10 times greater than the timber structure; or if the vibration period of the entire structure is not more than 1.1 times greater than the period of the wood framed portion of the building[15] (APEGBC, 2009). This feature is particularly relevant in a seismic country like Chile. An expansion using a wood frame or a steel frame system can result in two separate structures with different vibration periods under seismic loads. In this case there is a risk of collapse of the existing base of the expansion. However, CLT and Midply systems are based on shear walls that have high-resistance to shear stresses and stiffness similar to concrete structures. Thus, an expansion using CLT or Midply panels combined with the existing reinforced concrete structure could be considered as a single structure with the same vibration period (Figure 63).

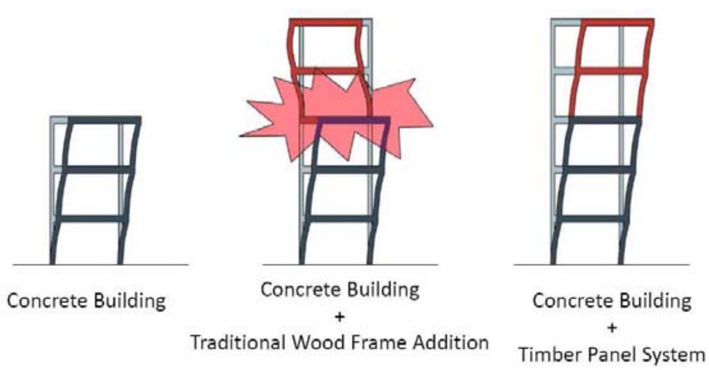

Figure 63: Seismic behavior of vertical expansions using standard platform frame systems and panel systems.

[15] This condition assumes that the wood framed portion of the building is a separate structure fixed at the top of the concrete level. Also concrete elevator shafts are much stiffer than wood paneled shearwalls and they will attract a disproportionate share of lateral forces if they are not structurally separated from the wood framing.

The first consideration of the design proposal is to define service cores and circulation cores as rigid elements in the layout of the building. New service cores are located over the existing ones to maintain existing utilities shafts. The Chilean Building Code requires two staircases for 7-storey or higher buildings. At least one of the circulation cores must be pressurized. Thus, one extra circulation core is added on the facade of the building (Figure 64).

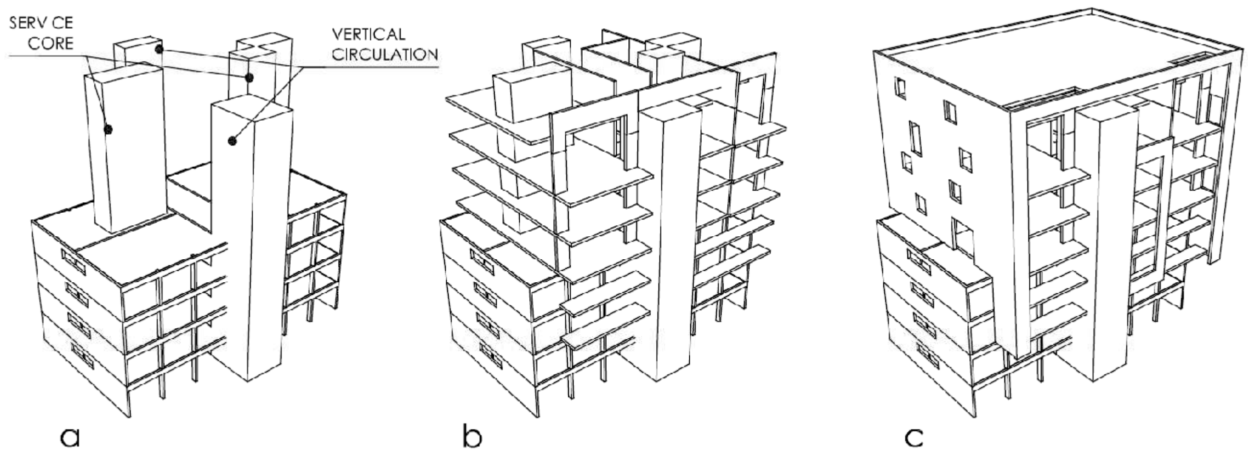

Figure 64: a) Service cores and vertical circulations as rigid elements. b) Lightness of timber systems allows the design of apartment plans independent from the existing layouts. c) The exterior enclosure ensures a proper climate control.

The symmetrical layout of the existing apartments does not respond to any site in particular or any climate conditions; the development of one typology of apartments does not allow a diversity of users. The lightness of timber systems allows the design of a new plan layout with the same orientation for all apartments. Fixed service cores are combined with undetermined spaces allow defining apartments according the particular needs of the residents (Figure 65).

The enclosure is conceived as a structural element that defines the expression of the building and its relation with the environment. This skin can adapt according the local weather through the addition of climate control elements such as louvers on the north façade. Terraces and balconies can be used as future expansions or as weather-control areas. They can provide shade in warm climates or can be closed in with glazing in cold climates to provide shelter from rain and create a greenhouse effect (Figure 66).

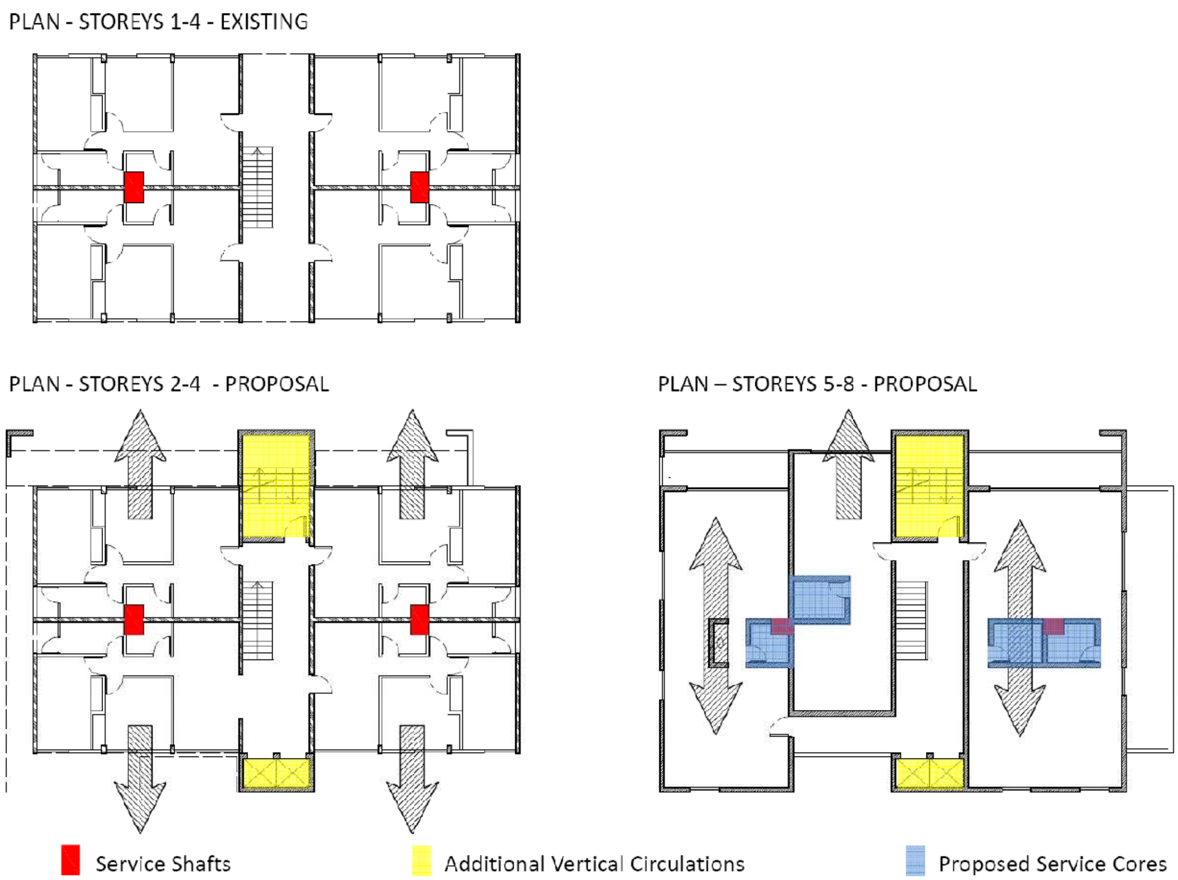

Figure 65: Plan layout of existing and proposed storeys. New apartments' layout is independent from the existing structure.

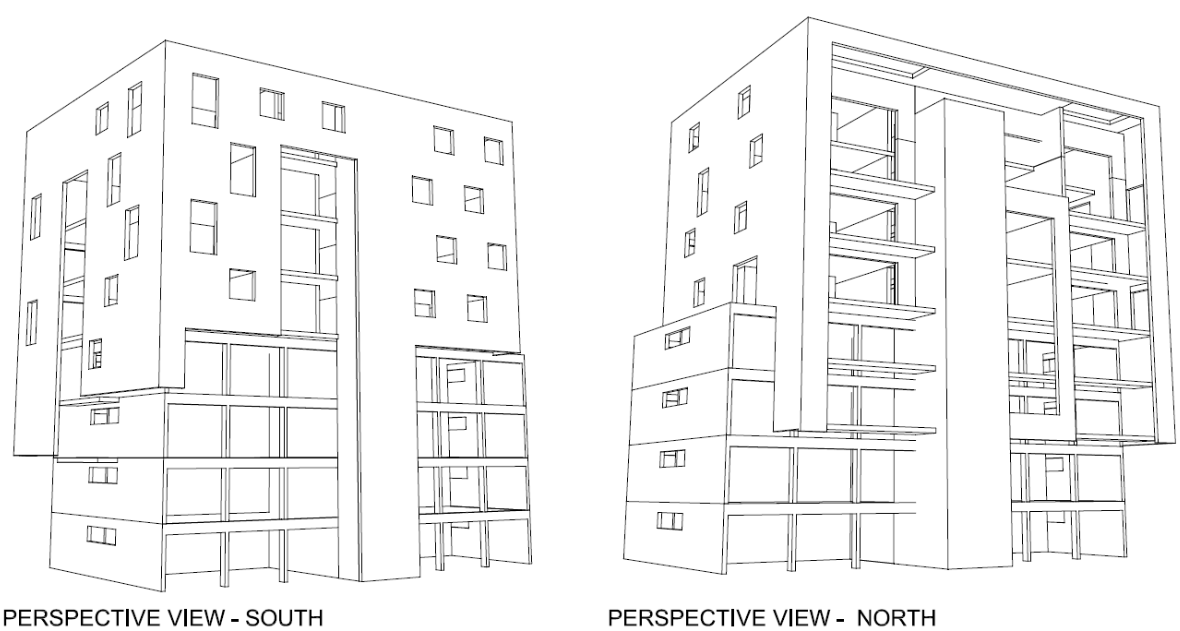

Figure 66: The enclosure is the main expression element of the building. Opening are design according its solar orientation.

The expansion enclosure creates gaps between the new structure and the existing building that enhanced the performance and quality of the existing apartments. This addition also has the possibility to positively impact the urban context where it is located (Figure 67).

Figure 67: The proposed expansion into the urban context.

5.4 Construction Details

As noted before, the proposal considers CLT or Midply panels as structural elements.

Construction details are developed considering thermal and fire performances of the assemblies according to the Chilean Building Code. Structural design is defined according to Northern Hemisphere standards as considerable modifications are required in the Structural Chilean Code for the feasibility of these systems in the local context.

Midply walls considered details similar to the common practice in wood frame structures in Chile. In order to meet the thermal requirements, 2-inch mineral wool is required in walls and 4-inch insulation is required in roof assemblies. Weather permeable barriers and vapor barriers are required to protect the timber from moisture. To meet fire resistance standards, double gypsum boards are added to walls and 40 mm concrete slabs are used as fire resistant elements.

The design of CLT construction considered the structural design criteria according to North American standards as the Chilean Structural Code is extremely restrictive for timber structures. Wall panels are structured in 3-layer panels on the upper 3 storeys and 5-layer panels on the bottom storey. In floor and roof slabs 5-layer panels are used. Considering Chilean lumber, thickness for CLT panels is 135 mm thick for 3-layer panels and 210 mm thick for 5-layer panels. The good thermal performance of massive timber meets the Chilean thermal requirements with no additional insulation in walls and only 2-inch mineral wool on the roof. According to fire performance certified alternatives, 5-layered CLT panels meet fire requirements (F-120). However, double gypsum boards are added to meet the fire resistance requirements for 3-layered panels. No vapor barrier is required (Figure 68).

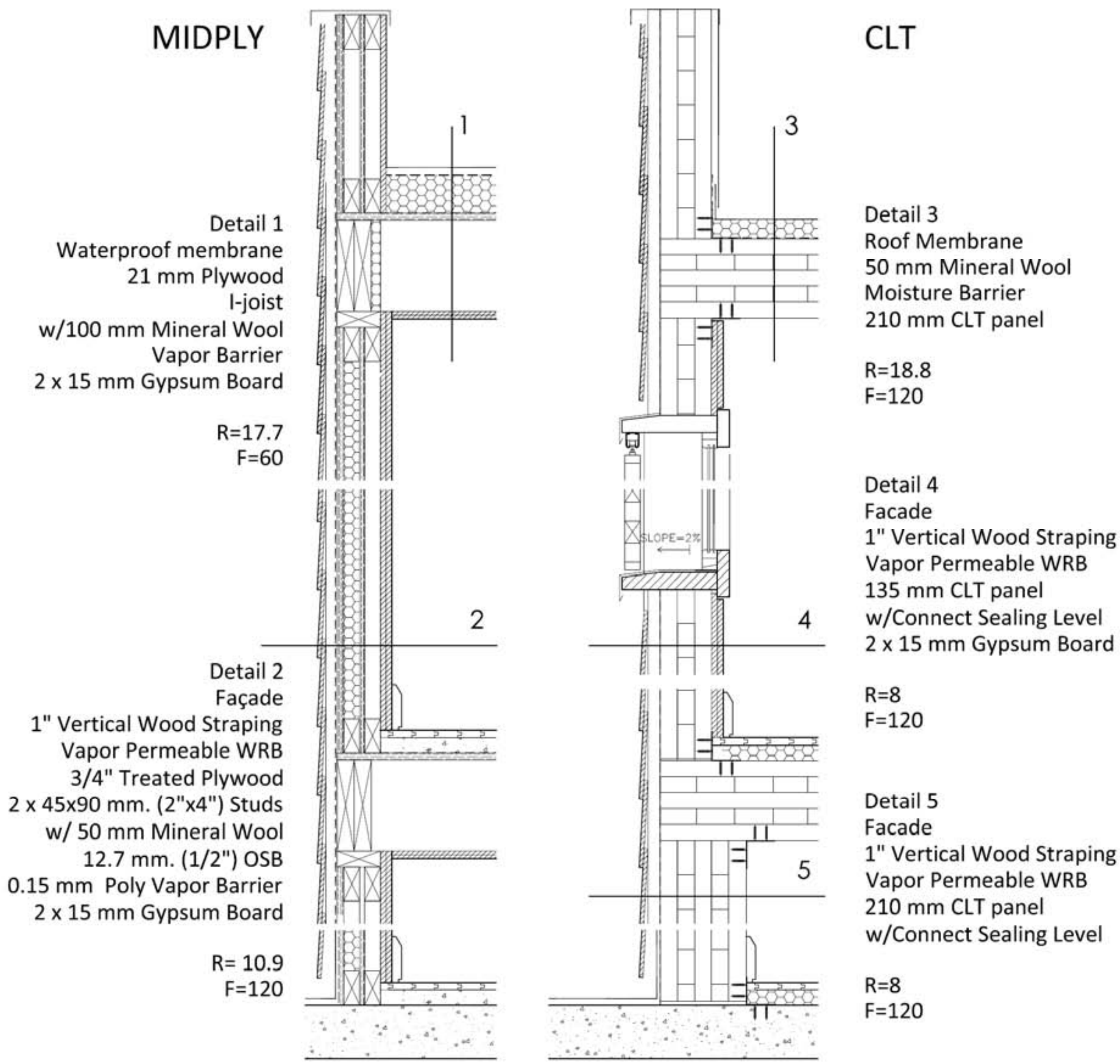

Figure 68: Section details of Midply and CLT systems applied to the case study.

6. Discussion & Conclusions

Today, new panel systems are changing the way architects conceive projects built in wood. Although current researches mainly focus on the structural performance of these systems, it is possible to analyze their application to the case of mid-rise buildings in Chile. To define the feasibility this study was based on implications of the resources availability, market feasibility, manufacturing feasibility, structural considerations and local building codes.

According to these variables, it is possible to conclude that both Midply and CLT systems are suitable for the Chilean context despite their different features. However, it is essential to modify the Chilean Structural Code in order to properly incorporate the seismic performance of timber structures for mid-rise structures. Moreover, specific structural codes are required for comprehensive seismic behavior of timber systems in general. Also, further research is needed on the application of softwoods and local construction techniques are required for timber panel systems in order to change the negative perception of users about timber housing.

It is also possible to conclude that the Chilean context has interesting design opportunities to develop buildings that use these systems. These prefabricated structures are flexible, light and have shear high-resistance. These features can be used to explore new and groundbreaking design alternatives. This research studied the expansion of reinforced concrete mid-rise housing. The project was challenging not only because the structural requirements, but because of the holistic development of the concept. Climate control and fire safety also define construction details and layout configurations that impact the design.

In summary, both Midply and CLT systems have structural and constructive features suitable for Chile that should be evaluated with a comprehensive development of a project. It is necessary further exploration on architectural possibilities that could expand the use of these systems.

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Appendix: Structural Calculations for a 4-storey Building in CLT According to the NCh-433

Juan Acevedo K. Ingeniero Civil	Proyecto : EDIFICIO 4 PISO EN MADERA Materia : ANALISIS SISMICO Fecha : FEBRERO /2012	Hoja 01 Calculo : JUAN ACEVEDO K Reviso: OAK

RESUMEN MEMORIA DE CALCULO

BASES DE CALCULO:

- DISEÑO DE ACUERDO CON ESPECIFICACIONES DE LA NORMA NCh 1198 OF 2006
- PROPIEDADES ADMISIBLES PARA PINO RADIATA SEGÚN PROYECTO CORFO e INFOR
- NORMA NCh 433 OF 2009 DISEÑO SISMICO DE EDIFICIOS
- NORMA NCh 1537 "DISEÑO ESTRUCTURAL DE EDIFICIOS CARGAS PERMANENTES Y SOBRECARGAS DE USO
- NORMA NCh 431 "CONSTRUCCION – SOBRECARGAS DE NIEVE"
- NORMA NCh 432 "CALCULO DE LA ACCION DEL VIENTO SOBRE LAS CONSTRUCCIONES" COEFICIENTE DE VIENTO SEGÚN DIN 1055 PARTE 4
- NORMA NCh 2150 "MADERA LAMINADA ENCOLADA – CLASIFICACION MECANICA Y VISUAL PINO RADIATA

MATERIALES

- MADERA LAMINADA ENCOLADA PINO RADIATA FABRICADA SEGÚN NCh 2148
- TENSIONES ADMISIBLES DERIVADAS SEGÚN NCh 2165

Appendix A: Structural Calculations for a 4-storey Building in CLT According to the NCh-433

Juan Acevedo K.	Proyecto : EDIFICIO 4 PISO EN MADERA	Hoja : 01
	Materia : ANALISIS SISMICO	Calculo : JUAN ACEVEDO K
Ingeniero Civil	Fecha : FEBRERO /2012	Reviso: OAK

RESUMEN MEMORIA DE CALCULO

BASES DE CALCULO:

- DISEÑO DE ACUERDO CON ESPECIFICACIONES DE LA NORMA NCh 1198 OF 2006
- PROPIEDADES ADMISIBLES PARA PINO RADIATA SEGÚN PROYECTO CORMA e INFOR
- NORMA NCh 433 OF 2009 DISEÑO SISMICO DE EDIFICIOS
- NORMA NCh 1537 "DISEÑO ESTRUCTURAL DE EDIFICIOS CARGAS PERMANENTES Y SOBRECARGAS DE USO
- NORMA NCh 431 "CONSTRUCCION – SOBRECARGAS DE NIEVE"
- NORMA NCh 432 "CALCULO DE LA ACCION DEL VIENTO SOBRE LAS CONSTRUCCIONES" COEFICIENTE DE VIENTO SEGÚN DIN 1055 PARTE 4
- NORMA NCh 2150 "MADERA LAMINADA ENCOLADA – CLASIFICACION MECANICA Y VISUAL PINO RADIATA

MATERIALES

- MADERA LAMINADA ENCOLADA PINO RADIATA FABRICADA SEGÚN NCh 2148
- TENSIONES ADMISIBLES DERIVADAS SEGÚN NCh 2165

Juan Acevedo K.	Proyecto : EDIFICIO 4 PISOS EN MADERA Materia : ANALISIS SISMICO	Hoja 02 Calculo . JUAN ACEVEDO K
Ingeniero Civil	Fecha : FEBRERO /2012	Reviso: JAC

- MEDIOS DE UNION : CLAVOS Y CAMARADES CONFORME A NCh 1198
- CONECTORES DE ACERO INDUSTRIALIZADO BULL-DOG DIMENSIONES Exx, UNILATERALES DE DIAMETRO XX, mm y Dxx, BILATERALES DE DIMENSIONES XX, mm
- ICHA "MANUAL DE DISEÑO DE ESTRUCTURAS DE ACERO"
- LEY DE ORDENANZA GENERAL DE URBANISMO Y CONSTRUCCION"
- PARAMETROS SISMICAS CAPITULO 4 SEISMIC PARA CLT

PARAMETROS DE DISEÑO.

UBICACION : PUCON

ZONA SISMICA : 1

CATEGORIA SUELO II (EDIFICIO HABITACIONAL SEGÚN NCh 433, PARRAFO 4.3.1)

SISTEMA ESTRUCTURAL : MUROS Y SISTEMA ARRIOSTRADO DE MADERA CLT.

ESTADOS DE CARGA :

PP : PESO PROPIO

SC : SOBRECARGA DE USO

Juan Acevedo K. Ingeniero Civil	Proyecto : EDIFICIO 4 PISO EN MADERA Materia : ANALISIS SISMICO Fecha : FEBRERO /2012	Hoja 03 Calculo : JUAN ACEVEDO K Reviso: JAK

METODO DE ANALISIS

ESTATICO, DEBIDO A QUE LA ESTRUCTURA ES CATEGORIA II Y ZONA SISMICA 1, NO SUPERIOR A 5 PISOS NI ALTURA MAYOR QUE 20 m

EN EL METODO DEL ANALISIS, LA ACCION SISMICA SE ASIMILA A UN SISTEMA DE FUERZAS CUYOS EFECTOS SOBRE LA ESTRUCTURA SE CALCULAN SIGUIENDO LOS PROCEDIMIENTOS DE LA ESTATICA

ESFUERZO DE CORTE BASAL

$$Q_0 = C \cdot I \cdot P$$

EN QUE:

C = COEFICIENTE SISMICO

$$C = \frac{2{,}75\, A_0}{g R} \left(\frac{T'}{T^*} \right)^n ,$$

n, T : PARAMETROS RELATIVOS ACTIVO DE SUELO DE FUNDACION SEGUN TABLA 6,3 DE NORMA

$n = 1{,}33$; $T' = 0{,}35$

A_0 = ACELERACION MAXIMA EFECTIVA, SEGUN TABLA 6,2

$A_0 = 0{,}20\, g$

Juan Acevedo K.

Ingeniero Civil

Proyecto: Edificio 4 Pisos Madera

Materia: Análisis Sísmico

Fecha: Febrero/2012

Hoja: 04

Calculo: Juan Acevedo K

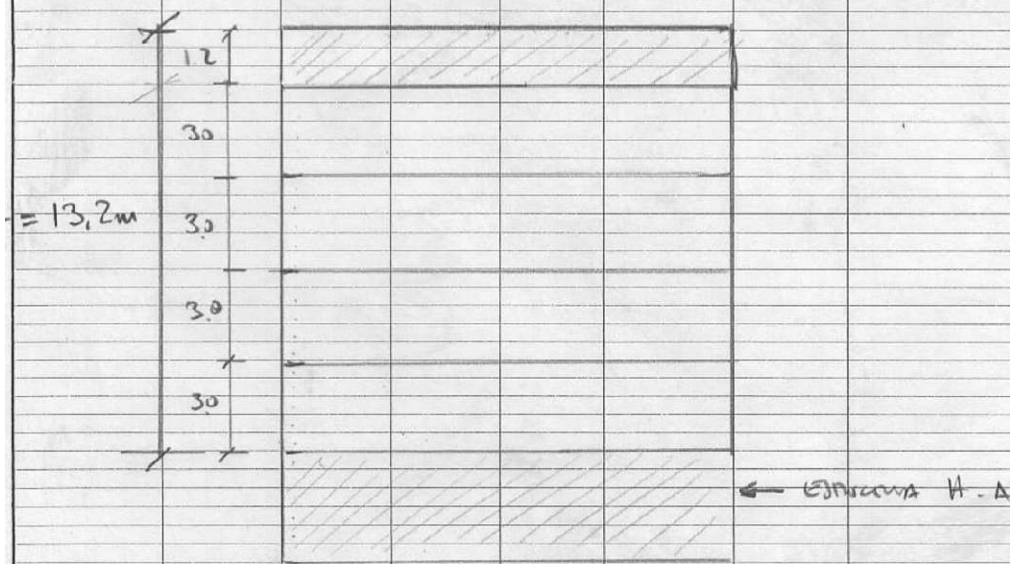
Reviso: JAK

R = Factor reducción que se establece en 5.7 de la norma

$R = 5.5$ (Madera) $R_0 = 7,0$

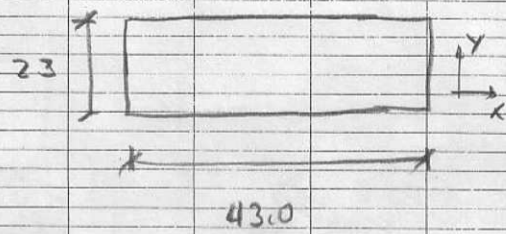
T^* = Período del modo con mayor masa traslacional equivalente en la dirección del análisis.

$$T^* = 0{,}024 \left(\frac{H}{\rho}\right)^{1/3} \; ; \; H = 13{,}2m$$ (altura total del edificio)



ρ = suma total del largo de muros en sentido del sismo para todo el edificio, dividido por el área total de las plantas de todo el edificio (m/m^2)

Juan Acevedo K.	Proyecto : Edificio 4 Pisos Madera	Hoja 05
	Materia : Análisis Sísmico	Calculo . Juan Acevedo K
Ingeniero Civil	Fecha : Febrero /2012	Reviso: JAR



Planta (asimilada)

Sup: 990 m² por piso

Sentido Y-Y (más desfavorable

$$h = \frac{1288}{3960} = 0,325$$

$$T^* = 0,024 \left(\frac{13.2}{0,325}\right)^{1/7} = 0,0407 \text{ seg}$$

Peso Propio.

Techumbre.

Cubierta —————— 12 kgf/m²

Estructura CLT h=22.6 cm —— 88 kgf/m²

Cielo volcanita —————— 10 kgf/m²

110 kgf/m²

Sobrecarga de techo ——— 60 kgf/m²

Juan Acevedo K.	Proyecto : EDIFICIO 4 PISOS MADERA	Hoja ..06..
	Materia : ANALISIS SISMICO	Calculo . JUAN ACEVEDO K
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MUROS CLT ——— 98 kgf/m²

PISOS ——— 148 kgf/m²

S CARGA NORMATIVA ——— 200 kgf/m²

LUEGO CARGA TOTAL :

i) $110 + 0{,}25 \times 60 = 125 \times 990 \times 1 / 1000 = 123{,}75$ TON

ii) $[98 \times 43 \times 4 + 98 \times 23 \times 7] \times 4 \times 3 / 1000 = 391{,}61$ TON

iii) $[148 + 0{,}5 \times 200] \times 990 \times 4 / 1000 = 982{,}08$ TON

1497,44 TON

LUEGO $C = \frac{2{,}75 \cdot 0{,}2\,g}{g \cdot 5{,}5} \left(\frac{0{,}35}{0{,}0407}\right)^{1{,}33} = 1.75$

Para $R = 5{,}5$; $S = 1{,}0$

$C_{min} = 0{,}4\, S A_0 / g = 0{,}4\,(1{,}0)\, 0{,}2\,g / g = 0{,}08$

LUEGO $Q_0 = 0{,}08 \times 1{,}0 \times 1497{,}44$

$= 119{,}79$

$Q_0 \simeq 120$ TON

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	Materia : ANALISIS SISMICO	Calculo . JUAN ACEVEDO K
Ingeniero Civil	Fecha : FEBRERO / 2012	Reviso: JAK

DISTRIBUCION SISMICA VERTICAL

K	Z_K (m)	Z_K/H	$1-\frac{Z_K}{H}$	$\sqrt{1-Z_K/H}$	A_K	P_K (TON)	$P_K A_K$	F_K	$T_K(K+1)$ [TON]
0	0,0	0,0	1.0	1.0	—	299	—	—	120.0
1	3,0	0.227	0.773	0.8792	0,1208	299	36,18	14.52	105,48
2	6.0	0.4545	0.5455	0.7385	0.1407	299	42,07	16,92	88,56
3	9.0	0.6818	0.3182	0.56409	0.17441	299	52,148	20,93	67.63
4	12.0	0.909	0.091	0.30166	0.26243	299	78,467	31,49	36,19
5	13.2	1.0	0,0	0.0	0.30166	299	90.19	36,19	—

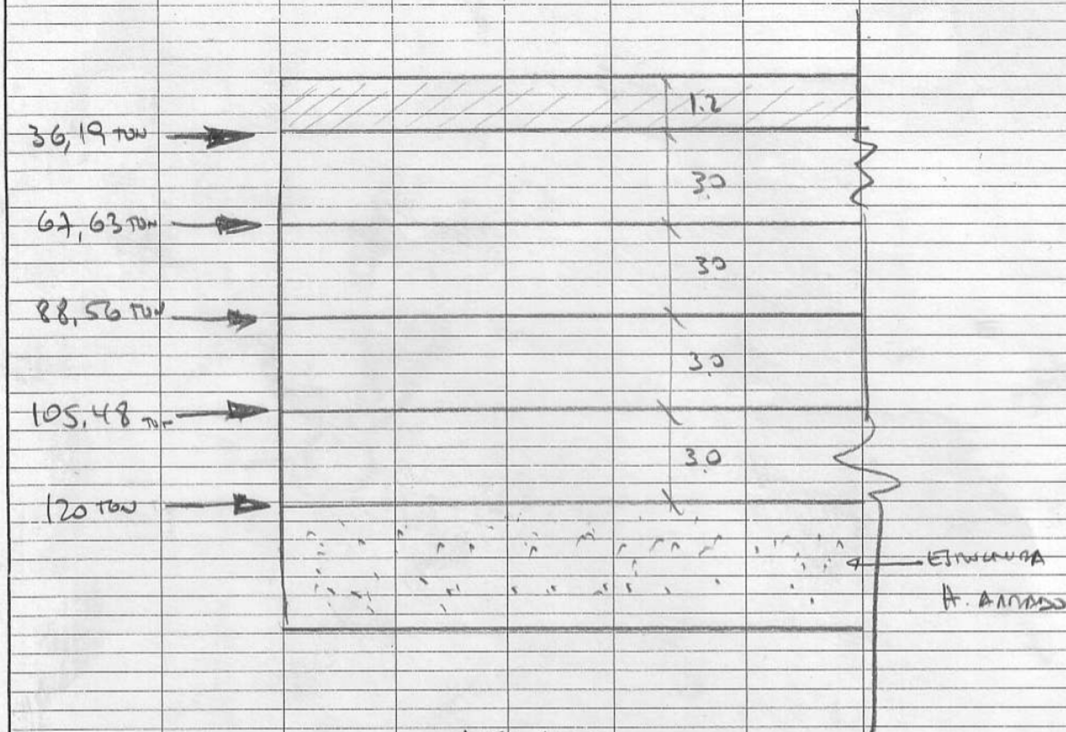
$\sum$ 299 $\sum$ 120,0

$$A_k = \sqrt{1 - \frac{Z_{k-1}}{H}} - \sqrt{1 - \frac{Z_k}{H}} \quad ; \quad \varphi = \frac{120}{299} = 0,401$$

$$\varphi = \frac{Q_0}{\sum_{j=1}^{5} P_j A_j} \quad ; \quad F_k = (P_k A_k)\,\varphi$$

$$T_{k(k+1)} = \sum F_k - \sum F_k$$ ESFUERZO DE CORTE ENTRE NIVEL.

Juan Acevedo K. Ingeniero Civil	Proyecto: EDIFICIO 4 PISOS MADERA Materia: ANALISIS SISMICO Fecha: FEBRERO /2012	Hoja 08 Calculo JUAN ACEVEDO K Reviso: JAK

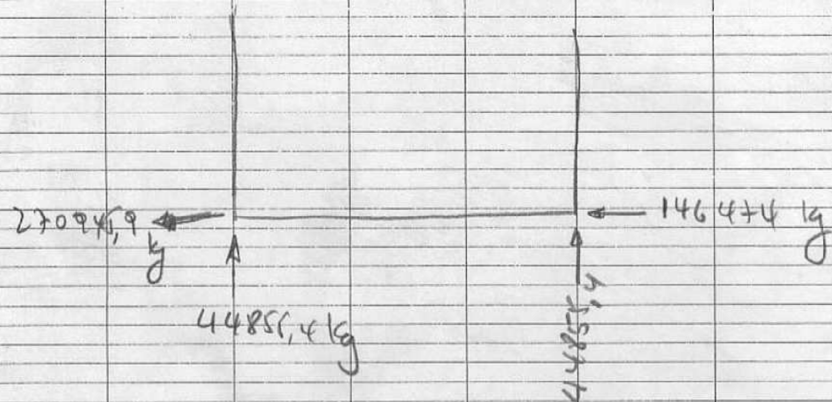


DE ACUERDO A NORMA NCh 433

EL DESPLAZAMIENTO RELATIVO ENTRE DOS PISOS CONSECUTIVOS, MEDIDO EN CUALQUIER PUNTO DE LA PLANTA EN CADA UNA DE LAS DIRECCIONES DE ANALISIS, NO DEBE EXCEDER EN MAS DE 0,001 h, AL DESPLAZAMIENTO RELATIVO CORRESPONDIENTE MEDIDO EN EL CENTRO DE MASAS, EN QUE h ES LA ALTURA DE ENTREPISO

LUEGO ES 3 MM VALOR MUY EXIGENTE PARA LA MADERA, ELEMENTO MAS FLEXIBLE

Juan Acevedo K.	Proyecto : Edificio 4 Pisos Madera	Hoja ...09
Ingeniero Civil	Materia : Análisis Sísmico	Calculo : Juan Acevedo K
	Fecha : Febrero / 2012	Reviso: JAK



Henrmie Zapato.

$V_{máx} = 44855,4$ kg

Atiesamiento

$b_{ef} = 22,6$ cm

$F_{cm_{des}} = 20$ kgf/cm²

$$L_{ap\,req} = \frac{V_{máx}}{F_{cn} \times b_{ef}} = \frac{44855,4}{20 \times 22,6} = 99,23 \text{ cm}$$

Se considera $L = 100$ cm.

Dimensionamiento placa base

$$f_{cq} = \frac{44855,4}{100 \times 30} = 14,95 \text{ kgf/cm}^2$$

Juan Acevedo K. Ingeniero Civil	Proyecto : Edificio 4 Pisos Marina Materia : Anclaje Sísmico Fecha : Febrero 2012	Hoja : 10 Calculo : Juan Acevedo K Reviso: GMC

$$M_{máx} = \frac{14,95 \times 15^2}{2} = 1681,87 \text{ kgf cm/m}$$

Sección rectangular acero A37-24ES

$$\rightarrow F_f = 0,75\, F_f = 1800 \text{ kgf/cm}^2$$

$$W_{req} = \frac{M}{F_f} = \frac{1681,87}{1800} = 0,934 \text{ cm}^3/\text{m}$$

$$t_{req} = \sqrt{0,934 \times 6} = 2,36 \text{ cm}$$

Uso $t = 25$ mm

Uso placa base