

CLT Handbook

CROSS-LAMINATED TIMBER

U.S.  EDITION

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FC Handbook

CROSS-LAMINATED TIMBER

U.S.  EDITION

Edited by
Erol Karacabeyli, P.Eng., FPInnovations
Brad Douglas, P.E., AWC

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Pointe-Claire, QC
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PREFACE

Expansion into mid-rise, high-rise and non-residential applications presents one of the most promising avenues for the North American wood industry to diversify its end use markets. This may be achieved by:

- Designing to new building heights with **Light Frame Wood Construction**
- Revival of **Heavy Timber Frame Construction**
- Adoption of **Cross-laminated Timber (CLT)**
- Facilitating **Hybrid Construction**

There are concerted efforts both in Canada and in the United States towards realizing that goal. In fact, the Canadian provinces of British Columbia and Quebec went even further and created specific initiatives to support the use of wood in those applications.

This Handbook is focused on one of these options – adoption of cross-laminated timber (CLT). CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications in Europe. The Research and Standards Subcommittee of the industry’s CLT Steering Committee identified CLT as a great addition to the “**wood product toolbox**” and expects CLT to enhance the re-introduction of wood-based systems in applications such as 5- to 10-story buildings where heavy timber systems were used a century ago. Several manufacturers have started to produce CLT in North America, and their products have already been used in the construction of a number of buildings.

CLT, like other structural wood-based products, lends itself well to prefabrication, resulting in very rapid construction, and dismantling at the end of its service life. The added benefit of being made from a renewable resource makes all wood-based systems desirable from a sustainability point of view.

In Canada, in order to facilitate the adoption of CLT, FPInnovations published the Canadian edition of the CLT Handbook in 2011 under the Transformative Technologies Program of Natural Resources Canada. The broad acceptance of the Canadian CLT Handbook in Canada encouraged this project, to develop a U.S. Edition of the CLT Handbook. Funding for this project was received from the Binational Softwood Lumber Council, Forestry Innovation Investment in British Columbia, and three CLT manufacturers, and was spearheaded by a Working Group from FPInnovations, the American Wood Council (AWC), the U.S. Forest Products Laboratory, APA-The Engineered Wood Association and U.S. WoodWorks. The U.S. CLT Handbook was developed by a team of over 40 experts from all over the world.

Both CLT handbooks serve two objectives:

- Provide immediate support for the design and construction of CLT systems under the alternative or innovative solutions path in design standards and building codes;
- Provide technical information that can be used for implementation of CLT systems as acceptable solutions in building codes and design standards to achieve broader acceptance.

The implementation of CLT in North America marks a new opportunity for cross-border cooperation, as five organizations worked together with the design and construction community, industry, universities, and regulatory officials in the development of this Handbook. This multi-disciplinary, peer-reviewed CLT Handbook is designed to facilitate the adoption of an innovative wood product to enhance the selection of wood-based solutions in non-residential and multi-storey construction.

Credible design teams in different parts of the world are advocating for larger and taller wood structures, as high as 30 stories. When asked, they identified the technical information compiled in this Handbook as what was needed for those applications.

A Renaissance in wood construction is underway; stay connected.

ACKNOWLEDGEMENTS

The great challenge with this U.S. Edition of the CLT Handbook was to gather experts from the United States, Canada and Europe to bring together their expertise and knowledge into a state-of-the-art reference document. The realization of this Handbook was made possible with the contribution of many people and numerous national and international organizations.

Such a piece of work would not be possible without the support from financing partners and, as such, we would like to express our special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution to this project.

First and most of all, we would like to express our gratitude to AWC, APA, USFPL, FPInnovations, U.S. WoodWorks and their staff for providing the effort and expertise needed to prepare this work. We would also like to express our special thanks to all chapter authors, co-authors, and reviewers who shared their precious time and expertise in improving this manual.

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Co-editors

CLT Handbook, U.S. Edition

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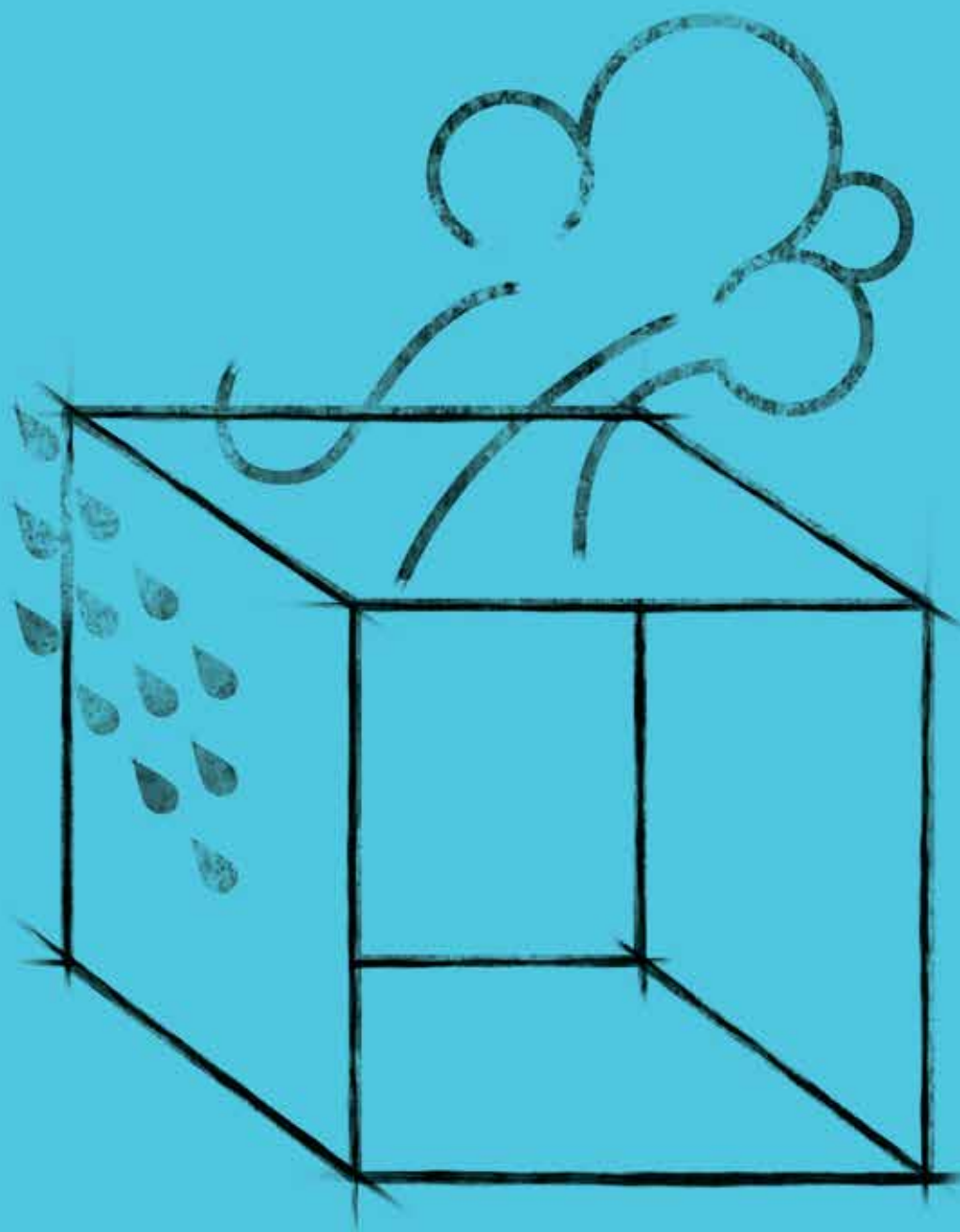
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ABSTRACT

Cross-laminated timber (CLT) was developed in Europe for the prefabricated construction of wall, roof, and flooring elements. Adaptation of CLT for use in the United States requires consideration of the different climates, building codes, and construction methods in this country.

Building enclosure design has important implications for the energy performance and durability of the structure as well as indoor air quality. The key performance requirements of the enclosure discussed in this Chapter are prevention of water intrusion and control of heat flow, air flow, and moisture flow. The use of prefabricated CLT panels does not change the basic heat, air, and moisture control design principles for an exterior wall or roof assembly. However, the design of CLT assemblies requires attention to the unique characteristics of this product. CLT panels are massive solid wood elements and therefore provide some level of thermal insulation, thermal mass, and airtightness (a separate continuous air barrier system is nevertheless recommended). CLT panels have a relatively high capacity to store moisture but relatively low vapor permeability. If exposed to excessive wetting during transport, storage on the jobsite, construction, or in building service, the panels may absorb a large amount of moisture, and the subsequent drying may be slower than it is for lightweight wood-frame construction.

This Chapter provides guidance on heat, air, and moisture control in wall and roof assemblies that utilize CLT panels in U.S. climate zones. The overarching strategies are to prevent wetting of CLT panels by using drained wall systems, to control airflow using an air barrier on the exterior of the CLT panels, to place rigid insulation to the exterior of the panels, to prevent moisture from accumulating within the panels, and to allow the panels to dry should they get wet. In certain climates, preservative treatment of CLT is recommended to provide additional protection against potential hazards such as decay and termites.

It is intended that these guidelines should assist practitioners in adapting CLT construction to U.S. conditions and ensuring a long life for their buildings. However, these guidelines are not intended to substitute for the input of a professional building scientist. This may be required in some jurisdictions and is recommended in all areas at least until such time as CLT construction becomes common practice.

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1 INTRODUCTION

Cross-laminated timber (CLT) was developed in Europe for the prefabricated construction of wall, roof, and flooring elements. Adaptation of CLT for use in the United States requires consideration of the different climates, building codes, and construction methods in this country.

CLT panels are typically constructed by laminating three or more layers of lumber together, with each layer oriented 90° relative to the neighboring layers (Figure 1). The lumber is most commonly adhered using a structural adhesive, with or without edge gluing between boards in the same layer. Manufacturing methods and lumber quality may have an impact on the final product properties but they do not affect the overall design strategy.



Figure 1

CLT panel constructed of three layers of cross-laminated board lumber to create a solid wood panel

Building enclosure design has important implications for the energy performance and durability of the structure as well as indoor air quality and occupant comfort. The key performance requirements of the enclosure discussed in this Chapter are prevention of water intrusion and control of heat flow, air flow, and moisture flow. The building enclosure serves a number of other functions, such as providing structural support for the building, controlling solar radiation, noise and fire, and providing an aesthetically pleasing finish. Many of these functions are discussed in other chapters of this Handbook.

Exterior wall and roof assemblies that use prefabricated CLT panels follow the same basic heat, air, and moisture control design principles as all building enclosures. The enclosure separates the interior environment of the building from the exterior environment, so it must handle loads such as precipitation, solar radiation, temperature gradients, humidity gradients, and air pressure differences. Building enclosure design must consider the outdoor climate as well as the intended building use and indoor environment. All building systems and materials can be compromised by water and air infiltration, and by vapor migration should it result in condensation or excessive

moisture levels. Whether it be steel, concrete, masonry, or wood frame, no construction system is immune from the effects of moisture-related problems. These problems can be avoided with thoughtful attention to water management principles and proper enclosure details. Wood has been successfully used to construct durable building enclosures for centuries.

As a building system, CLT has a number of unique characteristics. Prefabrication means that buildings can be constructed quickly, which may reduce the exposure of building components to wet weather. CLT panels have good thermal properties: their thickness provides some level of thermal insulation as well as thermal mass. Although CLT panels may have some inherent level of airtightness, an additional air barrier membrane is recommended (given the possibility that gaps between boards may develop as a result of drying-related shrinkage). The monolithic nature of CLT panels makes it possible to apply a single membrane as the water-resistive barrier and continuous air barrier. CLT panels have a relatively high capacity to store moisture but relatively low vapor permeability. If exposed to excessive wetting during construction or in building service, the panels may absorb a large amount of moisture, and the subsequent drying may be slower than it is for lightweight wood-frame construction.

CLT panels are not a cladding material and are not designed to be exposed to the exterior environment. They are a moisture sensitive structural assembly and therefore must be protected from rain and other moisture sources through the use of properly designed wall and roof assemblies.

This Chapter provides design guidance for CLT building enclosures in U.S. climate zones. The overarching strategies are to prevent wetting of CLT panels by using drained wall systems, to control airflow using an air barrier to the exterior of the CLT panels, to place rigid insulation to the exterior of the panels, to prevent moisture from accumulating within the panels, and to allow the panels to dry should they get wet. In certain climates, preservative treatment of CLT is recommended to provide additional protection against potential hazards such as decay and termites.

2

HEAT, AIR, AND MOISTURE CONTROL STRATEGIES

One of the primary functions of the building enclosure is the environmental separation between conditioned and unconditioned spaces. The enclosure should be designed to keep out liquid water, stop airflow between the interior and exterior, manage water vapor diffusion, and manage heat flow. These functions are important because heat, air, and moisture impact energy performance, durability, indoor air quality, and occupant comfort in all buildings. Several key wood properties are first addressed to provide a foundation for understanding the heat, air, and moisture control strategies for CLT enclosures.

2.1 Wood Properties Related to Heat, Air, and Moisture

Wood is a natural material that has been used successfully as a building material for centuries. Wood, if kept dry, does not deteriorate easily. As a natural material, wood is anisotropic and inhomogeneous; the properties can be different depending on the direction relative to the grain, and properties can also depend on which part of the tree the wood comes from (e.g., sapwood versus heartwood). Figure 2 shows the three principal grain directions in a piece of lumber. Wood shows larger variations in properties than most man-made building materials. The variations are usually larger between different wood species than within the same species. For example, Douglas-fir generally has lower density and lower permeability (higher resistance) to water and vapor movement compared with southern pine species. Softwoods, which are the species mostly used for construction as well as CLT manufacturing in North America (APA, 2011), generally have lower inter-species variations than hardwoods.

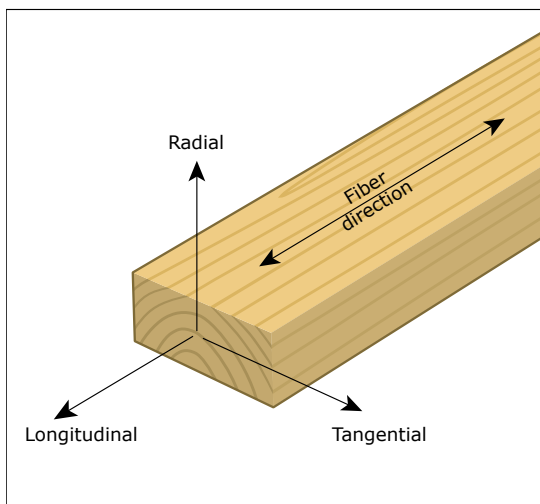


Figure 2

Three principal axes of wood with respect to grain direction and growth rings

The impact of wood property variations is manageable during design and construction. It is usually not possible or necessary to precisely evaluate the moisture and thermal properties of the specific material being used in building design. However, the understanding of these properties becomes more important to the design of CLT building enclosure assemblies than traditional wood-frame assemblies because of the massive solid wood nature of CLT. This section aims at providing generic physical properties of wood to help with CLT building enclosure design and related performance prediction using hygrothermal models.

2.1.1 Density and Specific Gravity

Density (or specific gravity) is one of the most important properties of wood related to building design. Density is defined as the mass of wood divided by the volume of the specimen at a given moisture content, usually expressed in $\text{lb}\cdot\text{ft}^{-3}$ ($\text{kg}\cdot\text{m}^{-3}$ or $\text{g}\cdot\text{cm}^{-3}$). Specific gravity is defined as the ratio of the density of a substance to the density of water at a specified reference temperature, typically 39°F (4°C), where the density of water is $62.43 \text{ lb}\cdot\text{ft}^{-3}$ ($1,000 \text{ kg}\cdot\text{m}^{-3}$ or $1.0 \text{ g}\cdot\text{cm}^{-3}$). If a wood specimen has a density of $31.2 \text{ lb}\cdot\text{ft}^{-3}$ ($500 \text{ kg}\cdot\text{m}^{-3}$ or $0.5 \text{ g}\cdot\text{cm}^{-3}$), it has a specific gravity of 0.5. The specific gravity of most softwood species ranges from 0.3 to 0.6. Specific gravity varies slightly with moisture content because wood undergoes dimensional changes with changing moisture content below about 28-30% (see Section 2.1.3). The values used in design specifications in North America are based on mass and volume under oven-dry conditions (AF&PA, 2005; CSA, 2009). The CLT manufacturing standard (APA, 2011) requires that softwood lumber species or species combinations used for CLT manufacturing have a minimum published specific gravity of 0.35, and that the same lumber species or species combinations be used within a single layer of CLT. The major softwood species or species combinations used for structures in North America, such as SPF (spruce-pine-fir), Hem-fir (hemlock-fir), southern pine, and Douglas-fir, all meet this requirement. The effect on density of the adhesive used to glue boards can be neglected due to the small amount of adhesive compared with the mass of wood.

Density or specific gravity has an important effect on all the physical properties of CLT, including thermal properties, as discussed in Section 2.1.4. The density or specific gravity of CLT can be further assessed based on methods developed for solid wood specimens such as ASTM D2395 (2007b), if the value is critical for building design or hygrothermal modeling.

2.1.2 Moisture Storage and Moisture Transfer

Moisture-related properties of wood are critically important for understanding and predicting the response of CLT building assemblies that are exposed to varying environmental conditions, including precipitation, temperature, humidity, and solar radiation. Understanding the moisture-related properties of wood is essential for designing CLT structures that avoid problems such as mold growth, decay, and dimensional changes.

2.1.2.1 Moisture Content and Fiber Saturation Point

Many physical and mechanical properties of wood vary with moisture content (Stamm, 1964; Siau, 1984; Skaar, 1988; USDA, 2010b). Moisture content is the ratio of the mass of water in wood to the mass of the oven-dry wood, usually expressed as a percentage. In living softwood trees, the moisture content of wood ranges from 30% to over 200%, depending on the species, growth season, and whether it is sapwood or heartwood. The wood starts losing moisture once a tree is cut. At the theoretical point when all the liquid water inside cells (“free water”) is gone but the cell walls are completely saturated with moisture (“bound water” adsorbed to the hygroscopic portions of the cell wall), the wood is considered to be at the fiber saturation point. This point averages about 28-30% on an oven-dry basis, varying by several percentages with wood species and other factors. In practice, the moisture content of wood is rarely homogeneous. Nevertheless, the fiber saturation point is considered as the critical moisture content in the relationships between moisture content and physical or mechanical properties, such as shrinkage and swelling, thermal and electrical properties, and strength. These properties change with moisture content only below the fiber saturation point.

2.1.2.2 Water Vapor Sorption

Wood is hygroscopic and has inherent moisture-storage capacity. It exchanges moisture with the surrounding air under ambient conditions. The amount of moisture gain or loss largely depends on the relative humidity but also on the temperature, drying history of the wood (wood can be made somewhat hydrophobic by intense drying or deliberate high-temperature treatment), and other factors. The loss of moisture is referred to as “desorption” and the gain of moisture as “adsorption”. When the wood no longer gains or loses moisture, it reaches equilibrium moisture content (EMC) under a specific set of environmental conditions. Figure 3 illustrates the relationship between EMC and relative humidity for a few selected temperatures (these curves are known as sorption isotherms). For example, at a temperature of 70°F (21°C), the average equilibrium moisture content is about 12% at a relative humidity of 65%; it decreases to 6% when the relative humidity is 30% and increases to 20.5% when the relative humidity is 90%. Water vapor sorption from air cannot bring the moisture content above the fiber saturation point. Higher moisture contents can occur only through condensation or exposure to other sources of liquid water.

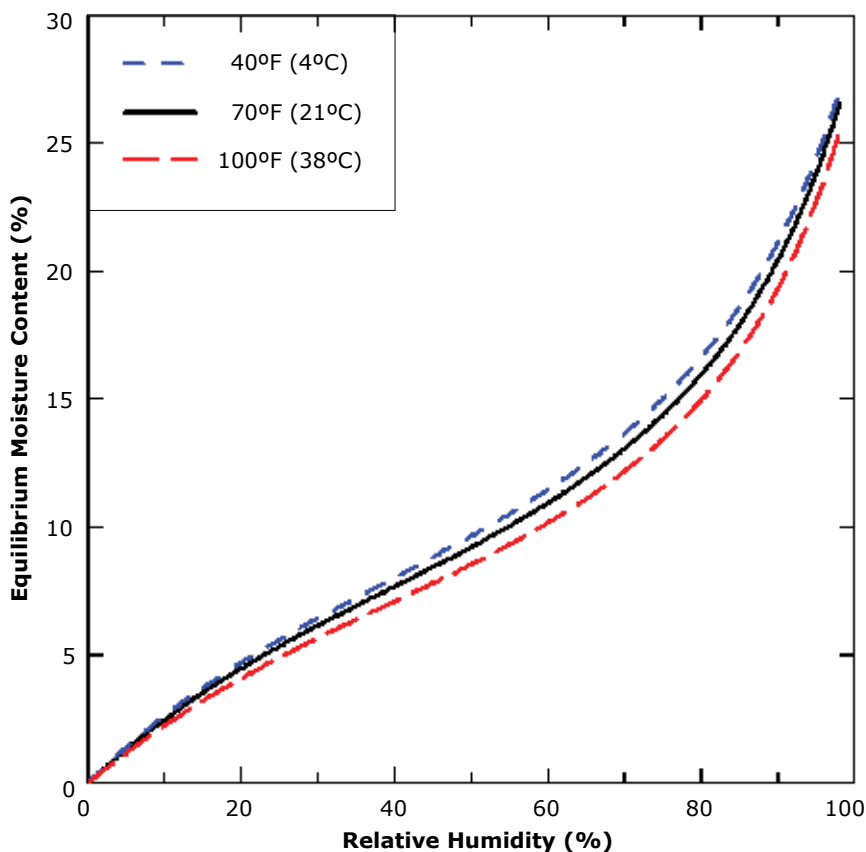


Figure 3

Generic sorption isotherms for wood from the Wood Handbook (USDA, 2010b)

In building service, wood is exposed to both long-term (such as seasonal) and short-term (such as daily) changes in relative humidity and temperature. As a result, the moisture content fluctuates within a range. Wood has a delayed response to changing environment, depending on its size, vapor permeability, the environmental conditions, and coatings or treatment. In a large CLT panel, the moisture content of the surface can change quickly, but it takes much longer time (weeks or months) for the center to show response to the changing environmental condition. The CLT manufacturing standard (APA, 2011) requires that the moisture content of lumber at the time of CLT manufacturing shall be $12\% \pm 3\%$. For structural composite lumber (lumber made from strands, flakes, or veneer), the moisture content shall be $8\% \pm 3\%$ at the time of CLT manufacturing. Typical EMCs of wood materials

within building enclosures are from 8% to 12%. This means that, to adjust to typical building service conditions, CLT panels exhibit only small changes in moisture content after installation, depending on the outdoor and indoor conditions. The hygric capacity of CLT can be advantageous in that CLT enclosures can buffer or accommodate short-term changes in humidity and temperature, unlike metal-framed enclosures. However, when CLT panels are subjected to extremely low or high levels of humidity or liquid water during installation and building service, wood may significantly lose or gain moisture. This will increase the risk of dimensional change-associated defects such as checking and warping and should therefore be avoided. Dimensional changes are discussed further in Section 2.1.3.

2.1.2.3 Water Vapor Permeability

Vapor permeability describes the rate of moisture transfer through a material under a gradient in water vapor pressure. This property can also be expressed as vapor permance for a given thickness (the reciprocal of vapor permance is vapor resistance).¹

This important property is associated with two major strategies of building enclosure design: to minimize moisture accumulation within the building enclosure, and to maximize drying capability by generally using materials with high vapor permeability. These two strategies may conflict, and it is important to coordinate them in design. Section 2.4 discusses control of water vapor diffusion in more depth.

Vapor permeability values in the literature are typically based on standard tests such as ASTM E96-05 (2005) using wet-cup and dry-cup methods. The vapor permeability of a number of solid wood species and wood-based products (e.g., plywood and oriented strand board) has been measured and incorporated into hygrothermal models. Two important trends are highlighted. First, vapor permeability increases with increasing relative humidity (or increasing moisture content). This is also generally observed for other hygroscopic materials such as building paper, plaster, and masonry. Second, at a given relative humidity, the vapor permeability of solid wood in the longitudinal direction (with the grain) is much greater than that in the transverse directions (across the grain). Vapor diffusion through the thickness of the CLT panel is across the grain, and measurements for this direction are given below. More rapid diffusion with the grain may be beneficial because it means that if wetting occurs at one location, moisture can be redistributed through the panel more quickly, which could allow faster drying.

Specimens as thick as full CLT panels are not suitable for testing according to standard test methods; however, thinner sections taken from CLT panels have been characterized. Figure 4 shows the vapor permeability of ¾ in. (19 mm) thick specimens cut from SPF and Hem-fir CLT panels, which include one layer of adhesive (NRC, 2012). The measurements were done through the panel thickness (across the grain). Just like solid wood or plywood, the vapor permeability of CLT increases with increasing relative humidity. Values range from 0.09 perm in. ($0.1 \text{ ng}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$) at 10% RH to 5.7 perm in. ($8.3 \text{ ng}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$) at 90% RH. It was observed that wood species or the type of adhesive used for CLT manufacturing did not have an appreciable effect on the vapor permeability.

¹The I-P unit for vapor permance is the “perm”; 1 perm is equivalent to $1 \text{ grain}\cdot\text{ft}^{-2}\cdot\text{h}^{-1}\cdot(\text{in. Hg})^{-1}$. At 73°F (23°C) where laboratory permance measurements are typically performed, $1 \text{ perm} = 57.4525 \text{ ng}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ (Thompson and Taylor 2008; note that the conversion from in. Hg to Pa is temperature dependent). The I-P unit for vapor permeability is the “perm inch”; 1 perm in. is equivalent to $1 \text{ grain}\cdot\text{in.}\cdot\text{ft}^{-2}\cdot\text{h}^{-1}\cdot(\text{in. Hg})^{-1}$. At 73°F (23°C), $1 \text{ perm in.} = 1.45929 \text{ ng}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$.

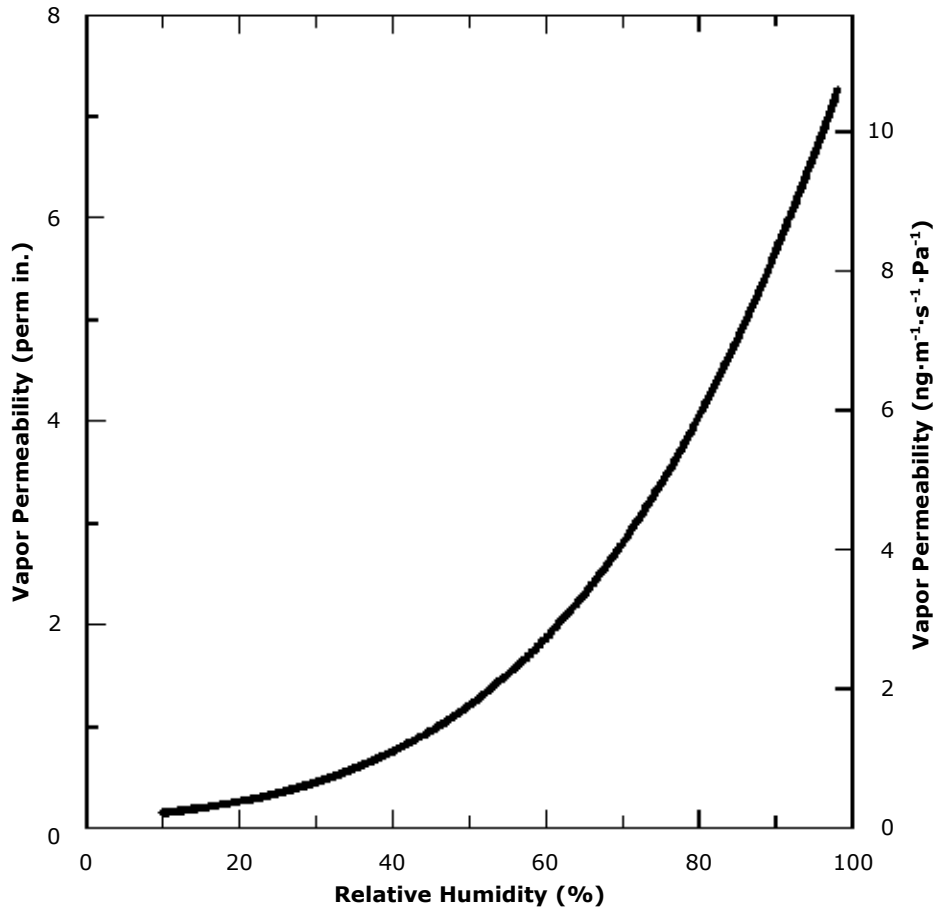


Figure 4
Water vapor permeability of CLT specimens (NRC, 2012)

Table 1 gives the vapor permeance values of CLT at different thicknesses. Based on these permeance values, typical CLT panels would be considered vapor impermeable or semi-impermeable and function as Class I or Class II vapor retarders in building enclosure assemblies based on the definitions of these terms adopted by the International Energy Conservation Code (IECC) (Lstiburek, 2006b). In many circumstances, no additional vapor retarder or barrier is therefore required to meet the building code (Gagnon et al., 2011). Note that the need for an air barrier is a separate issue (see Sections 2.1.5 and 2.3).

Table 1
Vapor permeance of CLT at different thicknesses and relative humidity levels (based on NRC, 2012)

Relative Humidity %	Vapor Permeance, U.S. perms (ng·m ⁻² ·s ⁻¹ ·Pa ⁻¹)		
	4 in. (100 mm)	6 in. (150 mm)	8 in. (200 mm)
20	0.06 (3.4)	0.04 (2.3)	0.03 (1.7)
50	0.31 (18)	0.21 (12)	0.15 (9.0)
80	1.00 (59)	0.68 (39)	0.51 (30)

2.1.2.4 Liquid Water Absorption

Wood absorbs liquid water (by capillary suction) when it is exposed to rain, condensation, or other wetting sources. The ability to absorb and the rate of absorption are closely associated with its permeability to liquid water, varying greatly with species, grain orientation, and prior history of wetting and drying. Such properties highly depend on the micro-structures such as the size of cells, pits (openings) between cells, and presence of extractives (Stamm, 1964; Siau, 1984; Skaar, 1988). For example, wood tends to be less permeable when a high proportion of the pits are closed or plugged with extractives, as in the heartwood of many species. The sapwood of North American Western and Northern species or species combinations such as SPF, Hem-fir, and Douglas-fir generally has lower permeability than the sapwood of the southern pines, and the former species also have greater proportions of low permeability heartwood.

Compared with water vapor sorption, liquid water absorption can lead to rapid increase in moisture content. Therefore, exposure to excessive liquid water should be minimized during transport, storage, construction, and building service to prevent adverse impacts on durability. The same can be said in general for many other building materials. The actual moisture content that wood reaches when exposed to liquid water mostly depends on its permeability to liquid water. In highly permeable woods, the maximum moisture content (at which all the cell cavities are filled and which depends on porosity or density) may be reached in some parts of the material. For wood with low permeability, it is very difficult for water to penetrate deep into wood and fill every cell, even under high pressure conditions (Wang et al., 2012).

For a given specimen, water absorption is usually much more rapid in the longitudinal direction, i.e., through end grain, than in the transverse (radial and tangential) directions (Siau, 1984; Skaar, 1988). The implications for control of moisture during construction are discussed in Section 4. Water absorption rates can be measured by a method based on the International Standard ISO 15148 (2002). An associated index, liquid water diffusivity, is often calculated based on water absorption coefficients (Straube and Burnett, 2005).

2.1.3 Dimensional Changes

Wood shrinks when it loses moisture and swells when it gains moisture at moisture content below the fiber saturation point. Wood shrinks or swells more across the grain than lengthwise. Dimensional changes are greater in the direction of the annual growth rings (tangential), about half as much across the growth rings (radial), and usually very slight along the grain (longitudinal) (USDA, 2010b). For example, the average shrinkage of spruce from fiber saturation point to oven-dry state (with moisture content change from 30% to 0%) is about 7-8% in the tangential direction, 4% in the radial direction, and 0.1-0.2% in the longitudinal direction (USDA, 2010b). Wood used in construction and similarly in CLT manufacturing always has a mixture of growth ring orientations. It is recommended to use an average shrinkage coefficient of 0.2-0.25% per 1% change in moisture content for cross sections of most softwood lumber (Breyer et al., 2006; NIST, 2010). With care in manufacturing, transport, storage, and construction, the moisture content will only change within a small range, and consequently the shrinkage will be much smaller. For example, if the lumber has an average moisture content of 12% during CLT manufacturing and the equilibrium moisture content in service is 10%, the moisture content change is 2%, which is associated with potential shrinkage of around 0.4-0.5% in the thickness direction of the CLT panel. Although the potential shrinkage in the width direction of the individual boards would be the same as that in the thickness direction, the cross lamination of boards in CLT panels minimizes the in-plane dimensional changes due to the good longitudinal stability of the adjacent lamina, as in plywood (Carll and Wiedenhoef, 2009; CertiWood™, 2012). Experience with multi-story CLT buildings in Europe has shown that vertical shrinkage is typically only about 1/8 in. (3 mm) per story.

The shrinking and swelling of individual boards in CLT can cause warping and checking on the CLT panel surfaces if large moisture content changes occur. Research (Gereke et al., 2009) has shown that the use of thicker outer layers could result in increased cupping of the panel, and that careful arrangement of lumber with respect to its growth ring orientation may improve the dimensional stability of a CLT panel.

Wood undergoes thermal expansion in addition to the moisture-related dimensional changes discussed above. Wood expands when heated and contracts when cooled. This effect is considerably smaller than moisture-related dimensional changes. Under most conditions for buildings, dimensional changes in wood are dominated by moisture effects (USDA, 2010b).

2.1.4 Heat Storage and Heat Transfer

Heat (storage) capacity is the amount of energy required to increase the temperature of one unit of mass by one degree, often expressed in $\text{Btu}\cdot\text{lb}^{-1}\cdot^{\circ}\text{F}^{-1}$ (or $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$). The heat capacity of wood depends on the temperature and moisture content but is practically independent of density or wood species (USDA, 2010b). Density is important, however, when considering heat capacity on a volume basis (as opposed to a mass basis). More information about calculation and measurements of specific heat capacity is available in the literature (TenWolde et al., 1988; Kumaran et al., 2002; Carmeliet et al., 2003; ASHRAE, 2009; USDA, 2010b). Compared with light-frame construction, the thermal mass of CLT can help moderate heating and cooling energy consumption in certain climates, as discussed in Section 2.5.

Thermal conductivity describes the rate of heat flow through a material under a gradient in temperature, often expressed in $\text{Btu}\cdot\text{in}\cdot\text{h}^{-1}\cdot\text{ft}^{-2}\cdot^{\circ}\text{F}^{-1}$ (or $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$). Thermal conductance for a given thickness is the thermal conductivity divided by thickness. Thermal resistance is the reciprocal of conductance, often expressed in imperial R-value ($\text{h}\cdot\text{ft}^2\cdot^{\circ}\text{F}\cdot\text{Btu}^{-1}$) or international system RSI ($\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$); these can be interconverted using $R = 5.678 \text{ RSI}$.

The thermal conductivity of wood depends on a number of variables, such as grain orientation, wood moisture content, and density. For building enclosure applications, heat flow is typically across the grain, and a moisture content of 12% is commonly assumed. The thermal conductivity of commonly used structural softwood lumber at 12% moisture content ranges from 0.7 to 1.0 $\text{Btu}\cdot\text{in}\cdot\text{h}^{-1}\cdot\text{ft}^{-2}\cdot^{\circ}\text{F}^{-1}$ (0.10 to 0.14 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) (TenWolde et al., 1988; ASHRAE, 2009; USDA, 2010b). This is much lower than other structural materials such as metals and concrete (about one twentieth that of steel), and it is only about 2 to 4 times that of common insulation materials. The measured thermal conductivity of CLT specimens made with SPF and Hem-fir (NRC, 2012) is consistent with the reported values of solid wood. CLT panels can add a fair amount of thermal resistance to building enclosure assemblies depending on thickness. Table 2 provides design R-values for softwood CLT panels of various thicknesses.

Table 2

Thermal resistance of typical softwood at various thicknesses and 12% moisture content

Thickness	1 in. (25 mm)	4 in. (100 mm)	6 in. (150 mm)	8 in. (200 mm)
R-value ($\text{h}\cdot\text{ft}^2\cdot^{\circ}\text{F}\cdot\text{Btu}^{-1}$)	1.25	5.00	7.50	10.00
RSI ($\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$)	0.22	0.88	1.30	1.80

2.1.5 Air Permeability

Air permeability refers to the rate of air flow through a material under a gradient in air pressure. This property can also be expressed as air permeance for a given thickness. Wood-based structural panels such as plywood and oriented strand board have inherent low permeability to air flow (Kumaran et al., 2002; Carmeliet et al., 2003; Lstiburek, 2006a). In wood-frame building enclosure assemblies, these panels can function as components in an air barrier system provided gaps between panels are properly sealed (i.e., with sheathing tapes or sealant). If CLT is to be used as the air barrier (which is not recommended here), the airtightness of CLT building enclosure assemblies will depend mainly on the joints between individual CLT panels, whether there are gaps between individual boards or layers, and whether checking and gaps between boards occur resulting from wood shrinkage (Gagnon et al., 2011; Skogstad et al., 2012). Based on the measurement of air permeability of CLT specimens made with different wood species using a modified ASTM C522-03 method (2009), the air permeability is

negligible provided no visible gaps or checking exist in the CLT specimen (NRC, 2012). However, gaps between boards within full size panels may develop, which could result in air flow. Section 2.3 discusses control of air flow in greater detail.

2.1.6 Moisture and Wood Durability

Durability of wood components in the context of this Chapter means resistance to biodeterioration. A number of biological agents including decay fungi and insects can attack wood and cause structural degradation under suitable conditions (Morris, 1998; Carll and Highley, 1999; USDA, 2010a). On a national scale in the United States, decay fungi are a larger threat than insects (including termites) (USDA, 2010a). The key conditions for fungi to grow in wood include suitable moisture conditions and suitable temperature. Generally, it requires free water inside wood cells for decay fungi to grow and progress. Research (Wang and Morris, 2010; Wang et al., 2010) has shown that decay fungi can colonise kiln-dried wood products if the moisture content rises to a threshold of 26%, which can be considered as the low end of fiber saturation point; it then takes months for detectable structural damage to occur under such marginal conditions. However, when there is more free water available with moisture content ranging from 40% to 80%, strength loss can occur rapidly (in weeks in some susceptible wood species). Preventing extended exposure to excessive moisture is the key to preventing decay throughout the service life of buildings. Compared with decay, mold growth occurs on surfaces and is more associated with the relative humidity of the environment and the surface relative humidity of building components. It does not affect wood strength. The infestation of insects may also require certain moisture conditions. Termites, in particular the Formosan subterranean termite (*Coptotermes formosanus*), can be very destructive to wood structures in areas with termite hazard (USDA, 2010a). However, methods exist to prevent termite infestation, and wood buildings have performed well in such areas.

Sapwood of all wood species has low natural durability. Heartwood is generally more durable than sapwood. Wood species vary widely in the natural durability of their heartwood (USDA, 2010a). The heartwood of SPF and Hem-fir species is not durable, while the heartwood of Douglas-fir and western larch is moderately durable. The heartwood of species such as western red cedar, California redwood (old growth) and yellow cedar has high natural resistance to decay. The heartwood of yellow cedar and California redwood (old growth) also has high resistance to termites. When the wood is not naturally durable enough to prevent attack by decay fungi or insects in building service, it can be treated with preservatives to improve long-term durability. Section 5 provides more information on preservative treatment.

2.2 Exterior Water Management

The most important function of the building enclosure is to keep water out. Water intrusion in buildings has long been a major cause of construction related defects, whether they be steel, concrete, masonry, or wood-frame buildings. No construction system is immune to the effects of moisture-related problems. These problems can be avoided with thoughtful attention to water management principles and proper enclosure details.

There are well-designed, well-built, and well-maintained wood structures that are centuries old and still in service today. As with all building materials and systems, care must be taken in the design and construction of CLT building systems to avoid moisture-related problems.

Water management starts with minimizing the amount of moisture brought into the building enclosure with the construction materials. As discussed above, moisture management protocols for CLT enclosures start at the time of manufacture. The APA (2011) standard governs panel moisture content at the time of manufacture. Applying water repellents to end grain of CLT panels and other wood-based materials may effectively retard liquid water absorption; however, film-forming coatings may also retard drying. With or without such treatment, CLT panels must be protected from water during shipping, storage, and construction. Section 4 addresses moisture control during construction in further detail. A number of references provide general guidance on moisture control in buildings (ASHRAE, 2009; Brock, 2005; HPO, 2011; Lstiburek, 2006c; Lstiburek and Carmody, 1994; Rose, 2005; Straube, 2012; Straube and Burnett, 2005; Trechsel and Bomberg, 2009).

2.2.1 Moisture Transfer Mechanisms

Understanding how building materials get wet and dry out is crucial to designing and building long lasting, durable enclosures. There are four major mechanisms of moisture movement in buildings:

1. Liquid water flow, such as gravity-driven water intrusion through enclosure leaks;
2. Capillary action, which is the movement of water within the spaces of a porous material due to the forces of adhesion, cohesion, and surface tension. This can occur when porous materials are wetted by precipitation or are in contact with wet ground;
3. Airflow, which carries water vapor. Infiltration refers to air leakage into the building through the enclosure; exfiltration refers to outward air leakage;
4. Water vapor diffusion, resulting from differences in water vapor pressure between indoor and outdoor environments.

All four of the mechanisms above can wet building components, but water intrusion is usually the largest source of wetting and the most important to address. Water intrusion can be prevented by proper design, detailing, and assembly of building materials as outlined later in the Chapter. However, building materials get wet, drying can occur by drainage, airflow, evaporation, and diffusion. The key to durability is to reduce wetting and promote drying.

The relationships between air flow, surface temperatures of building materials, insulation systems, vapor diffusion, and drying rates of materials and assemblies are complicated. Developing a working understanding of these interwoven relationships is necessary in order to design and build any structure that is durable, energy efficient, and healthy to live and work in. Air flow is discussed in further detail in Section 2.3, vapor diffusion in Section 2.4, and heat flow in Section 2.5.

2.2.2 Water Management Strategies for Walls

Water management for CLT construction generally follows the same principles used in wood-frame construction or in other construction types. Rainwater coming in contact with the building enclosure can follow a number of different pathways:

- being deflected away from the enclosure by a water-shedding structure or surface;
- bypassing the water-shedding surface and be drained away from the enclosure by way of a drainage cavity, water-resistive barrier (WRB), and flashings;
- being absorbed and stored by porous building materials (and possibly transferred by capillary action or diffusion to other materials in the assembly); or
- intruding past the enclosure into the building.

The building enclosure must be designed to prevent water intrusion into moisture-sensitive materials. Water management strategies are generally based on deflection, drainage, drying, and durable materials (Hazleden and Morris, 1999):

Deflection: The first priority is to deflect as much rainwater away from the building as possible before it has a chance to penetrate the building enclosure. Roof overhangs, kick-out flashings at roof-wall intersections, drip edges, and sloping surfaces direct water down and away from the enclosure.

Drainage: Create pathways for water to easily drain from the assembly so it has less time to be absorbed by building materials.

Drying: Design the enclosure with assemblies that have the capability to dry. The use of a ventilated cavity between the cladding and the rest of the assembly reduces moisture transfer from the cladding into the assembly and improves the drying potential of the assembly.

Durable materials: Select naturally durable wood species or use preservative-treated wood where necessary (see Section 5 of this Chapter).

Drainage and drying strategies are illustrated in Figure 5, which shows a ventilated and drained cladding system where the primary cladding and secondary drainage planes are provided in addition to ventilation behind the cladding.

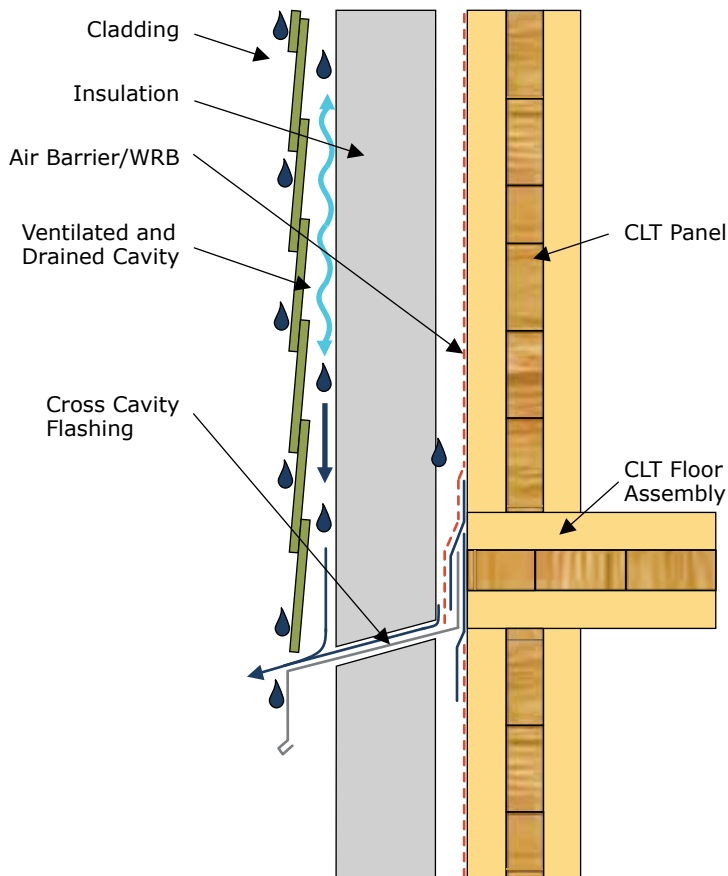


Figure 5
Best practice rainwater management strategy for CLT wall assembly

2.2.3 Approaches to Water Management in Exterior Walls

There are several approaches to water management for exterior walls, as described below.

2.2.3.1 Face-sealed Systems

The success of this approach requires perfect design, meticulous sealing of all penetrations and material interfaces at the exterior face of claddings, and a rigorous program of maintenance. This system is both labor and material intensive. It also is typically the least effective in the long term because expecting perfection is unrealistic and the system has no redundancy. If the sealant fails or separates from other materials as is common over the service life of the assembly, leaks will occur. Face-sealed systems are not recommended for CLT enclosures in any climate.

2.2.3.2 Storage or Mass Systems

This approach is traditionally used in thick stone or masonry walls. Water that does not drain away is absorbed and, in the absence of freeze-thaw cycles, safely retained until it can evaporate. The assembly must have sufficient safe moisture storage capacity (with no deterioration) to prevent moisture from being transmitted all the way to the interior. This approach is clearly not appropriate for CLT construction.

2.2.3.3 Drained Wall Systems

This approach assumes that claddings leak and that some water will breach the cladding. This system requires a water-resistive barrier (WRB) and drainage plane that is skillfully integrated in shingle fashion with window, door, through-wall, and all other flashings in order to drain water by gravity to the exterior. A 1/16 in. (1 mm) gap was shown to provide drainage reasonably well (Straube and Smegal, 2007). Adhered veneers, such as adhered masonry veneer, stucco, or stone often require two layers of WRB to allow drainage and prevent buildup of hydrostatic pressure. Three-dimensional “drainage wraps” and matrix materials can also aid in drainage and prevent inward moisture movement by capillary action. When rigid foam insulation is placed to the exterior of the WRB, use of a “drainage wrap” or grooves cut in the back of the foam insulation can enhance drainage and facilitate drying by diffusion (Lstiburek, 2010a). WRBs are described further below.

2.2.3.4 Drained and Ventilated Wall Systems

An important variation on the drained wall system is commonly known as a “rain screen”. This system employs a cavity directly behind the cladding, which creates a larger path for gravity drainage and allows ventilation airflow for improved drying (Figure 5). Rain screen systems are considered the most effective for drainage of water and for drying of transmitted moisture. They are required by the building codes for the wet-climate coastal areas of Canada and many other countries. The unfilled air space separates the cladding from the WRB and the structural wall assembly behind it. This air cavity promotes drainage and provides a capillary break to eliminate absorption of water into inner enclosure materials. This cavity also allows for airflow which further helps to dry the cladding and the rest of the wall assembly if it gets wet (Hazleden and Morris, 2001). A ventilated rain screen cavity can be designed to be pressure moderated, which reduces the potential for water being transmitted into the assembly by pressure differentials across the cladding. The most common example of a rain screen system in the United States is brick masonry veneer with the code required drainage cavity, as well as through-wall flashing and weep holes for drainage and ventilation.

The choice between a simple drained wall system and a rain screen system may depend on a variety of factors. A primary consideration is the amount of wind-driven rain to which walls are exposed, which depends on climate, building height, and roof design. Taller buildings generally have higher exposure to wind-driven rain than shorter buildings. Exposure of walls to wind-driven rain generally decreases as the extent of roof overhang increases, particularly for low-rise buildings. The drying potential of the climate is another consideration. In addition to these factors, a practical consideration for walls with exterior insulation is attachment of the cladding system.

2.2.4 Cladding Systems

Many different cladding systems can be applied using a rain screen system. For cladding attachment, continuous vertical furring (strapping) strips can be screwed through the rigid insulation to the CLT panel and the cladding can then be attached to the furring with short fasteners (CCHRC, 2009; Baker, 2012). Depending on loading conditions, a structural analysis of this cladding attachment scheme may be required. The gap between the furring strips creates an air space behind the cladding, which is beneficial for both drainage and ventilation. This air space should then be at minimum vented and drained (opened at the bottom) or ideally ventilated and drained (i.e., by providing openings in the cladding at both the top and bottom).

The practice of back-ventilating sidings such as wood, hardboard, and cement board is strongly recommended by most manufacturers to better ensure the stability and long-term performance of their products. It is also beneficial to provide an outlet for moisture driven inward by solar heating from more absorptive claddings such as brick, stucco, stone, and other porous materials.

The extent of airflow and drying capability in a ventilated cavity depend in part on the net free area of vent openings. For example, claddings attached to ¾ in. (19 mm) strapping, such as wood siding, cement board, or stucco applied over backer board, with continuous vents at top and bottom have much higher ventilation rates than brick veneer with a 1 in. (25 mm) cavity and weep holes spaced every two bricks at top and bottom (Burnett et al., 2004; Finch and Straube, 2007).

The cladding surface will shed the majority of the rainwater load on the wall; however, it is not the only line of water penetration resistance. Moisture that does penetrate past the cladding will either run down the backside of the cladding, the strapping, the surface of the exterior insulation if present, or the final line of protection, i.e., the lapped and sealed WRB. Any moisture that penetrates the cladding must then be drained back out of the assembly using flashings attached to the CLT panel behind the WRB at floor levels and around penetrations such as windows.

2.2.5 Water-resistive Barriers

The function of the WRB in a drained wall system is to prevent water that has bypassed the cladding and exterior insulation from intruding further into the wall. The WRB is an essential part of the drainage plane. This protective barrier must be properly overlapped between sheets, and integrated with window flashings and other flashings to shed water to the exterior. It must also be sealed at all plumbing, mechanical, electrical, and structural penetrations. Section 3 provides a series of details showing integration of the WRB with such flashings.

In most cases, the same material can function as the WRB and the air barrier, as discussed further in Section 2.3. A number of different materials can do this: self-adhered membranes, fluid-applied membranes, or mechanically-fastened building wraps (such as a non-perforated polyolefin membrane). Primary considerations in selecting a WRB are its resistance to liquid water and resistance to airflow. An additional consideration is vapor permeance of the WRB/air barrier, which is discussed in Section 2.4. Vapor permeable products promote faster outward drying of CLT assemblies, should they get wet during transport, storage, or construction. Perforated building wraps are not recommended because they are less resistant to water intrusion and do not qualify as air barrier materials.

2.3 Control of Air Flow

After stopping water intrusion, stopping air flow is the most important job of the enclosure because moving air carries heat and water vapor. Uncontrolled air leakage through the enclosure can cause unwanted heat loss or heat gain as well as unwanted moisture accumulation or interstitial condensation, which can lead to mold growth or even decay. Air leakage can thus negatively impact building energy performance, durability, indoor air quality, and occupant comfort.

Air flows are driven by differences in air pressure. A number of different physical forces can create air pressure differences:

- Wind and the associated airflows around the outside of a building create complicated pressure fields. The outside of the building is typically at positive pressure relative to the inside of the building on the windward side and at negative pressure on the leeward side;
- The stack effect refers to buoyancy caused by differences in air density between indoor and outdoor air. Air density (at a given barometric pressure) depends primarily on temperature: warm air has a lower density than cold air. In cold weather, warmer indoor air leaks out at the top of the building and cold air infiltrates at the bottom. In hot weather, the opposite occurs in air-conditioned buildings: warmer outdoor air leaks in at the top and cooler indoor air leaks out at the bottom. Stack effect pressure depends on the height of the building; it increases as buildings get taller;
- Mechanical equipment for heating, ventilation, and air-conditioning (HVAC) can also create air pressure differences across the enclosure. For example, fans for exhaust or supply air ventilation and duct leakage can create pressure imbalances across the enclosure.

Stopping air flow through the enclosure requires a continuous air barrier system over the entire building enclosure, which includes roofs, walls, and floors. Such a system can be made up of a series of overlapping and sealed materials, each with high resistance to air flow (low air permeance). It is essential that the system be continuous to minimize air leakage at interfaces between different materials. As mentioned in Section 2.1.5, measurements have shown that CLT panels themselves initially can have extremely low air permeance. If the CLT panels are to be used as part of the air barrier assembly within a building (not recommended here), appropriate measures such as flexible sealant joints between CLT panels and other elements of the air barrier assembly would be required for air barrier continuity.

The issue of whether CLT panels remain airtight in service has not been determined yet. Gaps between individual boards or layers and checking in boards may occur due to dimensional changes during storage, transportation, and construction as a result of drying or cyclical wetting and drying. It is reasonable to expect that manufacturing processes such as edge-gluing between boards help improve the long-term airtightness of the panels. However, in most cases, it would be prudent not to rely on the CLT panels themselves being the primary air barrier.

Considering that CLT panels must be protected with a water-resistive barrier (see Section 2.2), it is recommended that the WRB serve as the primary air barrier as well. The effective implementation of the air barrier system would then rely on the details to achieve continuity at exterior wall penetrations such as windows or doors, as well as at interfaces with floors, ceilings, balconies, decks, roofs, interior partitions, and various structural, mechanical, electrical, and plumbing penetrations. The details for such transitions would be similar to those used in traditional wood-frame construction.

Air sealing from the inside is also an option, using gypsum board with sealants or gaskets, sometimes referred to as the airtight drywall approach. However, this approach is not preferred as the primary air barrier because of the difficulty of executing a continuous seal at the interior, which typically has many intersecting materials.

Moving air carries water vapor along with it. If uncontrolled, this could lead to moisture accumulation in building enclosure assemblies by either of the following two ways:

1. Exfiltration during cold weather—humid indoor air leaks out and moisture accumulates in cold CLT members. Making the enclosure airtight and placing the thermal insulation to the exterior of the CLT practically eliminates the chances of this occurring. CLT panels stay warm and dry when insulation is to the exterior (see Section 2.5);
2. Infiltration during hot, humid weather—humid outdoor air leaks in and moisture accumulates in CLT panels, which are colder than outdoors because of air-conditioning. An air barrier system on the exterior side of the CLT minimizes the chances of this occurring. As previously discussed, a practical solution is to use a continuous membrane on the exterior of the CLT that functions as an air barrier and water-resistive barrier.

An airtight building must be provided with a mechanical ventilation system for ensuring indoor air quality. Further information about ventilation can be found in the *ASHRAE Handbook – Fundamentals* (ASHRAE, 2009). Local building codes typically address ventilation requirements.

2.4 Control of Water Vapor Diffusion

The two key strategies for moisture control in buildings are 1) to prevent materials from getting wet; and 2) to maximize their capability for drying in the event they do get wet. Other sections of this Chapter deal with preventing CLT panels from getting wet during construction (Section 4), during building service by liquid water (precipitation or capillary action, see Section 2.2) or by water vapor carried by airflow (Section 2.3). This Section deals with vapor diffusion, addressing its role in both wetting and drying.

Given the importance of vapor diffusion for drying, it is generally desirable to make CLT enclosure assemblies vapor permeable. The vapor permeability of CLT increases with increasing relative humidity, as depicted in Figure 4 and discussed in Section 2.1.2. This property is advantageous in the sense that when CLT gets wet, moisture transfer occurs at a faster rate, enabling redistribution of moisture and drying. However, this drying capability should not be relied on as a justification for allowing CLT to get wet. Therefore, the designer should evaluate the potential impacts of using low-permeance materials in building enclosures incorporating CLT. Decisions regarding the exterior insulation and WRB/air barrier, for instance, may benefit from project-specific hygrothermal analysis. Low-permeance materials will impede drying but may be necessary in some cases for preventing moisture accumulation in CLT.

Moisture accumulation in CLT could potentially occur by either of the following two ways:

1. During cold weather (in heating-dominated climates), when indoor vapor pressure is greater than outdoor vapor pressure (outward vapor drive), moisture might accumulate at the cold side of the assembly if the rate of diffusion into the assembly exceeds the rate of diffusion out of the assembly. In lightweight wood-frame construction, the phenomenon can occur in the exterior sheathing (OSB for example) if the interior side is too vapor-permeable and the insulation is placed in the stud cavity. However, when exterior insulation is placed outside the OSB in a wood-frame wall, the OSB sees a higher temperature and lower moisture content. CLT exterior walls differ from wood-frame walls in that vapor diffusion through CLT is much slower than through gypsum board and fibrous insulation, slow enough that it does not lead to high moisture levels. As in log home construction, the massive nature of a CLT panel will control the rate of vapor flow through the assembly. As shown previously in Table 1, the vapor permeance of a softwood CLT panel 4 in. (100 mm) thick or greater is less than 0.5 U.S. perms ($29 \text{ ng}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$) at normal indoor humidity levels (typically less than 60% RH). Moreover, field and laboratory research as well as hygrothermal modeling indicate that, in cold climates, no additional interior vapor retarder is needed to prevent excessive moisture levels in CLT walls with exterior insulation (Lepage, 2012; McClung et al., 2012). In summary, CLT walls are expected to perform very well in cold climates when insulation is to the exterior and there is no additional interior vapor retarder;
2. During warm, humid weather, when outdoor vapor pressure is greater than indoor vapor pressure (inward vapor drive), moisture might accumulate if the interior side of the assembly is too low in permeance relative to the exterior side of the assembly. In wood-frame construction, this problem has been observed when low-permeance materials such as polyethylene or vinyl wall covering are used on the interior. It is critical that inward drying not be impeded. Laboratory research and hygrothermal modeling have shown that CLT walls, with vapor-permeable exterior insulation and a vapor-permeable interior finish, are expected to perform well in a hot, humid climate (Goto et al., 2011). Hygrothermal modeling by the authors (unpublished data) of CLT walls with non-reservoir claddings in hot, humid U.S. locations confirms this finding.

However, inward vapor drive can be magnified considerably when the cladding acts as a moisture reservoir. Reservoir claddings include brick veneer, stone veneer, stucco, uncoated cement board, uncoated wood, etc. The phenomenon of solar-driven inward moisture diffusion in walls with such absorptive claddings is well-documented (Derome, 2010). In some cases, coatings may be used to limit rain absorption in such claddings. The magnitude of the inward vapor drive also depends on the climate—for example, the amount of wind-driven rain that hits the wall, whether the rain occurs significantly during the warmer months of the year, and how quickly solar irradiance increases after rain. Much of the eastern United States has such weather patterns. Inward vapor drives are most significant in the southeastern United States, but can also be significant even in the upper Midwest and Northeast, as discussed below.

Two methods are generally recommended to limit inward moisture flows from reservoir claddings: 1) back ventilation of the cladding; or 2) placement of a non-moisture-sensitive, low-permeance material between the cladding and the rest of the assembly, such as extruded polystyrene insulation. Back ventilation of claddings is achieved by creating a cavity between the cladding and the rest of the assembly that is open to airflow (see Section 2.2). Brick veneer, for example, is typically installed with a drainage cavity and weep holes. Air exchange rates in brick veneer cavities are typically much smaller than in cavities that have larger openings at top and bottom, such as wood siding or cement board installed on furring strips (Burnett et al., 2004; Finch

and Straube, 2007). Back ventilation may not be a reliable strategy for brick veneer constructed using common practice, given the lower air exchange rates and the possibility of localized areas where mortar bridges the cavity. Adhered veneers such as stucco and manufactured stone veneer can be installed on backer board over furring strips to create a ventilated cavity.

For brick veneer and for other reservoir claddings that are not installed with a ventilated cavity, the designer should consider the second method—use of a low-permeance material between the cladding and the rest of the assembly. This material could be the exterior insulation or the WRB/air barrier. For CLT assemblies, a vapor permeable WRB/air barrier membrane is desirable, specifically to allow drying of construction moisture (prior to installation of exterior insulation and cladding) and to allow drying in service when conditions are favorable. Therefore, the use of vapor semi-impermeable exterior insulation is preferred when reservoir claddings are used in climates with significant wind-driven rain during warm weather. The interior of the enclosure assembly should be vapor permeable to allow inward drying.

In the absence of field or laboratory research on CLT assemblies with reservoir claddings, hygrothermal modeling was used to establish conservative initial guidance on appropriate vapor permeance of exterior insulation for preventing moisture accumulation in CLT panels (assuming a vapor permeable WRB/air barrier). CLT wall assemblies clad with brick veneer or regular Portland cement stucco were simulated by the authors with three different types of rigid exterior insulation in eight U.S. cities. The three types of exterior insulation differ considerably in vapor permeability. Table 3 provides a vapor permeance classification for materials (based on Lstiburek, 2006b). Rigid mineral wool insulation is highly vapor permeable. The vapor permeance classes for expanded polystyrene (EPS) and extruded polystyrene (XPS) depend on thickness (and also on density) (BSC, 2007). At 1 in. (25 mm) thick, unfaced EPS is typically considered vapor semi-permeable; it transitions from semi-permeable to semi-impermeable at roughly 3 in. (76 mm) thickness. At 1 in. (25 mm) thick, unfaced XPS is considered borderline semi-permeable/semi-impermeable and is semi-impermeable at greater thicknesses. Rigid polyisocyanurate insulation (not simulated) is typically foil-faced; this facing makes it vapor impermeable.

For hygrothermal modeling, an insulation thickness was selected for a given climate to provide an effective R-value which, in combination with the R-value of 4 in. (100 mm) thick CLT, would be equivalent to the effective R-value required of wood-frame construction as per the IECC (ICC, 2009). As a criterion for acceptable performance, the exterior insulation was considered appropriate if simulated wood moisture content remained below 19% on a 30-day average basis throughout the entire CLT thickness. Table 4 summarizes the simulation results.

Table 3

Vapor permeance categories (Lstiburek, 2006b)

Designation	Vapor Permeance Range	Vapor Retarder Class
Vapor impermeable	0.1 perm or less	Class I vapor retarder (considered a vapor barrier)
Vapor semi-impermeable	1.0 perm or less and greater than 0.1 perm	Class II vapor retarder
Vapor semi-permeable	10 perms or less and greater than 1.0 perm	Class III vapor retarder
Vapor permeable	Greater than 10 perms	Not considered a vapor retarder

Table 4

Appropriate types of exterior insulation for CLT wall assemblies with vapor permeable WRB and poorly-ventilated or non-ventilated reservoir claddings

City	Climate Zone	Exterior Insulation Type		
		Extruded Polystyrene	Expanded Polystyrene	Rigid Mineral Wool
Miami	1A	Yes	No	No
Houston	2A	Yes	No	No
Atlanta	3A	Yes	Yes	No
San Francisco	3C	Yes	Yes	Yes
Seattle	4C	Yes	Yes	Yes
Boston	5A	Yes	Yes	No
Minneapolis	6A	Yes	Yes	No
Anchorage	7	Yes	Yes	Yes

Hygrothermal simulation by the authors (unpublished data) suggests that extruded polystyrene insulation is appropriate in conjunction with poorly-ventilated or non-ventilated reservoir claddings in all the climates investigated. Its resistance to vapor diffusion essentially protects CLT from inward vapor drive. Foil-faced polyisocyanurate insulation (not simulated) would be expected to perform similar to extruded polystyrene. Expanded polystyrene is appropriate in all locations except the hot humid Southeast (zones 1A and 2A). Finally, rigid mineral wool insulation is appropriate in western U.S. locations (San Francisco, Seattle, Anchorage). These locations typically see precipitation during colder months and dry weather during warmer months, so inward vapor drives are fairly weak. Cold climates such as Boston (5A) and Minneapolis (6A) see enough wind-driven rain in the warmer months for rigid mineral wool insulation to be potentially problematic in conjunction with a vapor permeable WRB and poorly-ventilated or non-ventilated reservoir claddings.

Hygrothermal modeling also indicates several other important trends.

- The issue of inward vapor drive becomes less significant when a well-ventilated reservoir cladding is selected, such as wood siding, cement board, or stucco applied over backer board, attached to ¾ in. (19 mm) strapping with continuous vents at top and bottom. Inward vapor drive is even less significant when a ventilated non-reservoir cladding is selected, such as painted wood, metal, or vinyl. That is, lower permeance on the exterior is not needed to prevent moisture accumulation in CLT in any climate with well-ventilated reservoir claddings or non-reservoir claddings. From a vapor diffusion perspective, all of the insulation types mentioned above are appropriate with well-ventilated reservoir claddings and non-reservoir claddings, assuming CLT panels are dry to begin with;
- Outward drying capability improves as the vapor permeance of the exterior insulation increases; CLT wall assemblies have less outward drying capability with vapor semi-impermeable exterior insulation than with vapor permeable exterior insulation;
- In any climate, outward drying capability is greater with a non-reservoir, ventilated cladding than with a ventilated reservoir cladding; similarly, outward drying capability is greater with a ventilated reservoir cladding than with a non-ventilated reservoir cladding.

In summary, vapor diffusion can be important in both wetting and drying. In general, given the low vapor permeance of CLT itself, it is desirable to maximize the drying capability of CLT assemblies by selecting vapor permeable materials for the WRB/air barrier and thermal insulation and a vapor permeable interior finish. When using poorly-ventilated or non-ventilated reservoir claddings in certain climates, impermeable or semi-impermeable exterior insulation is preferred to prevent moisture accumulation in CLT from inward moisture diffusion (Table 4). However, low-permeance exterior insulation will reduce the outward drying ability, and wetting during construction and in service must be minimized. An alternative method to prevent moisture accumulation in CLT from inward moisture diffusion is to specify a low-permeance WRB/air barrier. For example, if rigid mineral wool exterior insulation (which is vapor permeable) is desired for fire resistance, a low-permeance WRB/air barrier may be necessary in certain climates when using poorly ventilated or non-ventilated reservoir claddings. If rigid foam insulation is incorporated in CLT construction, the fire code provisions pertaining to foam plastic insulation will need to be addressed (see Chapter 8 of the CLT Handbook).

2.5 Control of Heat Flow

Thermal insulation is used to minimize heat loss or gain through the building enclosure. Air leakage control is also a key element of heat flow control as discussed previously (Section 2.3).

Being laminated solid wood, CLT inherently offers a fair amount of thermal resistance. R-values were previously given in Table 2 (Section 2.1.4). For a CLT panel made from typical softwood species, the panel provides an R-value of approximately R-1.25 per inch (i.e., R-5 for a 4 in. thick panel). Additional insulation is generally required for the wall assembly to meet local energy code requirements or the particular energy performance goals for a given building. It is recommended that insulation be placed to the exterior of the CLT panel (Section 2.5.1). CLT panels also provide thermal mass (Section 2.5.2).

2.5.1 Reasons for Exterior Insulation

The preferred location for placing insulation in CLT assemblies in all climates is to the exterior. There are several reasons why exterior insulation is preferred over interior insulation. First, placing the insulation to the exterior allows the insulation to be continuous, whereas interior insulation would be discontinuous where floors or interior walls intersect the exterior walls or roof. Continuity of insulation is important for reducing thermal bridging and improving energy performance. Second, exterior insulation shields the CLT structure and the air barrier system from temperature extremes (Lstiburek, 2010b). That way, these components see conditions that are close to the indoor environment, meaning less expansion and contraction. Third, exterior insulation capitalizes more on the thermal mass benefit of CLT panels (Section 2.5.2). Fourth, the placement of the insulation can significantly affect the moisture levels and durability of CLT panels in service. For cold climates, exterior insulation keeps the wood in a relatively constant warm and dry indoor environment. Warmer wood surfaces translate into lower surface relative humidity and less potential for microbial growth. As discussed in Section 2.3, exterior insulation minimizes the chance of moisture accumulating in CLT from air exfiltration during cold weather. For hot, humid climates, exterior insulation keeps the CLT closer to the drier indoor environment. Exterior insulation also improves the inward drying capability of CLT. The selection of exterior insulation type in relation to climate and type of cladding is discussed in Section 2.4.

2.5.2 Dynamic Thermal Performance and CLT Thermal Mass

CLT panels, both in the building enclosure and in interior floors and walls, can act as thermal mass that stores heat during the day and releases it at night. Thermal mass can reduce heating and cooling peak loads, shift the time of peak loads, lower overall building energy use, and enhance occupant comfort. The effectiveness of thermal mass can depend on a variety of factors: climate; building geometry and orientation; solar heat gains; internal heat generation; density, amount, location, and surface area of the mass; and rate of heat transfer into the mass.

The benefit of CLT thermal mass was investigated by the authors through hourly building energy simulation (unpublished data). The space conditioning energy savings from thermal mass of CLT were determined relative to

light-frame construction for two building types in nine locations. The building types include a two-story single-family dwelling (1,860 ft.² or 173 m²) and a four-story multi-unit residential building (40 suites; 31,000 ft.² or 2,880 m²). In order to isolate the effect of thermal mass, both the CLT and light-frame version of each building type are identical in terms of effective R-values for the enclosure, airtightness, occupancy, fenestration, lighting, and systems for heating, ventilation, and air-conditioning. (Effective R-values followed the 2009 IECC for the single-family dwelling and ASHRAE 90.1-2007 for the multi-unit residential building.) CLT enclosures were modeled with exterior insulation having an R-value that, in combination with the R-value of the CLT, was equivalent to the effective R-value of the code referenced enclosure. It should be noted that the results apply only to the specific buildings modeled, and simulation results can be sensitive to many inputs. Energy performance of a particular building in a particular location should be gauged through specific modeling.

Figures 6 and 7 depict energy savings for the CLT structures relative to the light-frame structures for each building type. Savings are separated into heating energy, cooling energy, and energy use for operation of fans. These are each expressed as a percentage savings for the CLT structure relative to the space conditioning energy use (heating + cooling + fans) of the light-frame structure of the same type. Heating Degree Days (HDD) and Cooling Degree Days (CDD) are also plotted for each location (65°F basis). The figures show that CLT thermal mass has some benefit in all locations, though the greatest benefit is seen in mixed climates (e.g., Sacramento and Atlanta). Energy savings from CLT thermal mass tend to be greater during seasons when outdoor temperatures fluctuate above and below indoor temperature. The energy savings for the CLT two-story single-family dwelling in a given location are greater than for the four-story multi-unit residential building. This is likely because the latter has a lower enclosure to floor area ratio and a greater intensity of internal heat gains; in addition, a greater portion of the space conditioning load is for ventilation.

Figure 8 shows the percentage reduction in the peak cooling load from CLT thermal mass for both types of buildings. CLT thermal mass is beneficial in all locations (except Fairbanks, where cooling was not included in the model). Again, the peak load reduction is greater for the single-family dwelling than for the multi-unit residential building for the reasons mentioned above. In summary, CLT thermal mass can provide significant savings in both space conditioning energy use and peak cooling loads.

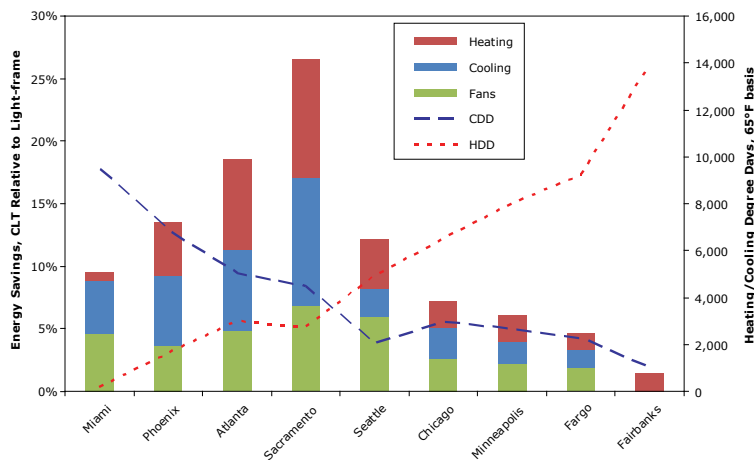


Figure 6 Space conditioning energy savings from CLT thermal mass for a two-story single-family residence (left axis), with heating and cooling degree days (right axis)

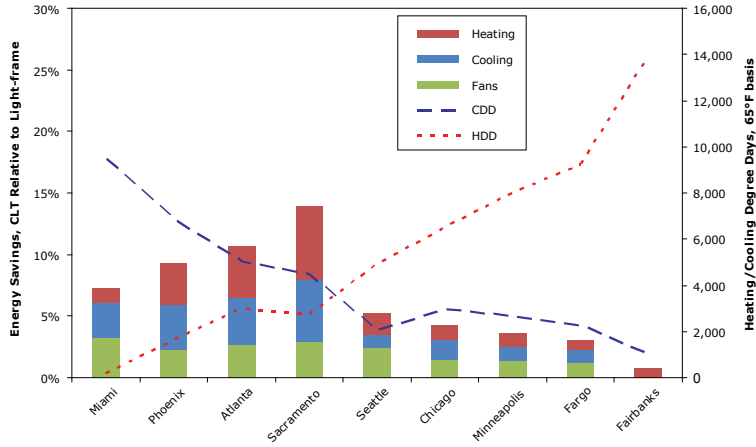


Figure 7
Space conditioning energy savings from CLT thermal mass for a four-story multi-unit residential building (left axis), with heating and cooling degree days (right axis)

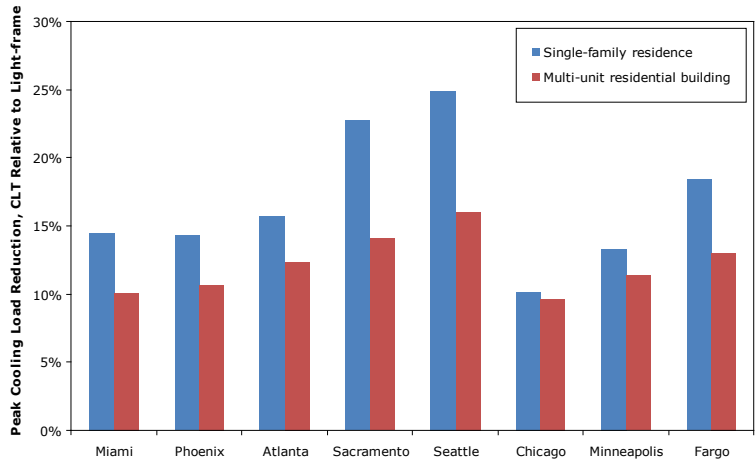


Figure 8
Peak cooling load reduction from CLT thermal mass for a two-story single-family residence and a four-story multi-unit residential building

3

RECOMMENDED BUILDING ENCLOSURE CONCEPTUAL DESIGN²

3.1 Exterior Wall Assemblies

Figures 9 and 10 depict a CLT assembly where the exterior insulation is sufficiently rigid (extruded polystyrene, expanded polystyrene, polyisocyanurate, rigid mineral wool)³ to allow that furring strips be screwed directly through it onto the CLT panel with minimal compression. In this assembly, a continuous vapor permeable WRB/air barrier membrane is applied before the rigid insulation is placed on the exterior of the panel. Vertical furring such as strips of plywood or 1x4 in. lumber are fastened directly through one layer of insulation to the CLT panels with screws of sufficient length to provide attachment points for the cladding, assuming this meets the structural requirements of cladding attachment (CCHRC, 2009; Baker, 2012). This assembly is the most thermally efficient of those illustrated in this Handbook. The space between the furring strips is left open to provide drainage behind the cladding, and openings are provided at the top and bottom of the wall for ventilation of the cavity. The assembly shown does not contain gypsum drywall on the interior. Where required for fire safety and acoustic control purposes, gypsum drywall would be fastened to the CLT panels or supported on vertical furring strips to allow for wiring and other services to be concealed.

Figures 11 and 12 illustrate two alternate cladding support strategies. Figure 11 shows two strapping members attached through the insulation to the CLT panels. The first strapping member would typically be a 2x2 in., and the second member a 2x2 in. or a size that suits the thickness of insulation. The first strapping member is attached to the CLT panels with screws through the rigid insulation, and the second is then attached to the first strapping member. This method may be necessary where greater thicknesses of insulation are required. It also offers benefits for detailing around penetrations and allows the insulation to be installed with staggered joints. Depending on the weight of the cladding system and the insulation thickness, a structural analysis may be necessary for the fastening system.

Given that the cavity is designed to drain liquid water that intrudes past the cladding, wood furring members placed to the exterior of the WRB/air barrier may require protection with some level of wood preservative depending on the exposure and local building code requirements. Attention should be given to the selection of appropriate corrosion resistant fasteners suitable for use with the preservative chosen for wood treatment.

Figure 12 shows a cladding support strategy using low conductivity spacers that are attached with screws to the CLT wall, providing rigid support to hang exterior vertical girt and cladding. In comparison to a system with metal clips that pass through the exterior insulation layer, this approach reduces thermal bridging.

²It is not at all sufficient for designers and specifiers to simply provide the construction trades with the text or the conceptual drawings shown in this section as instruction on moisture management detailing.

³If rigid foam insulation is incorporated in CLT construction, the fire code provisions pertaining to foam plastic insulation will need to be addressed (see Chapter 8 of the CLT Handbook).

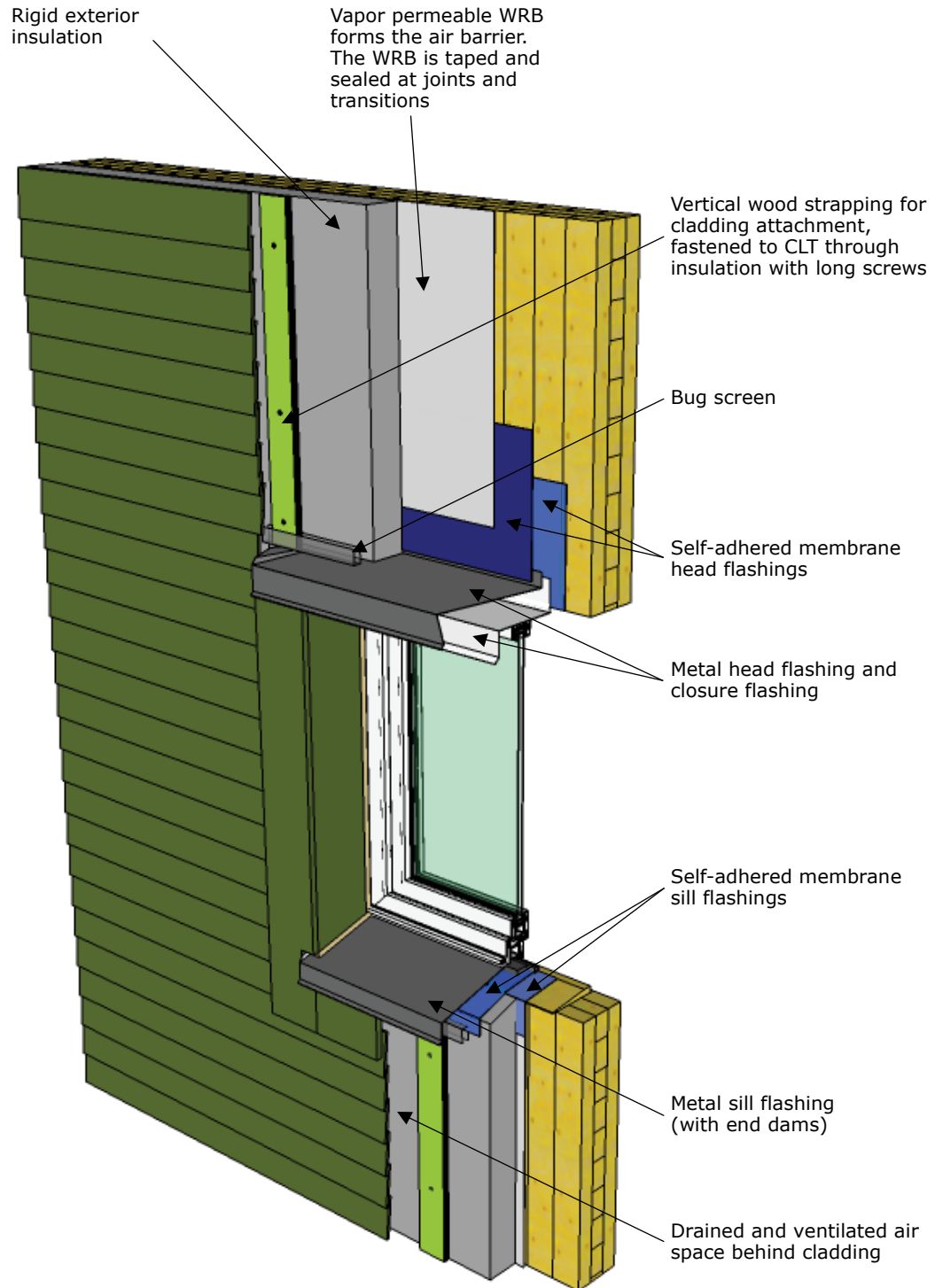


Figure 9
 CLT exterior wall assembly with exterior insulation and ventilated cladding, showing material sequencing and schematic window flashing details

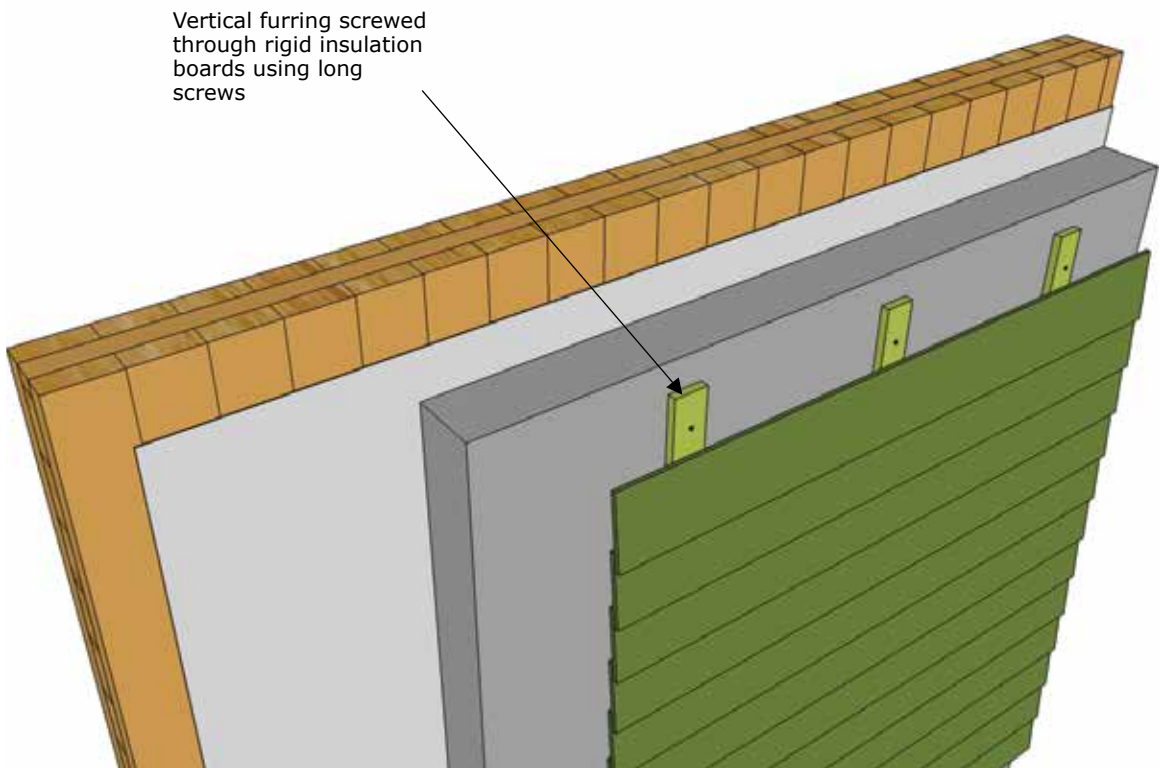


Figure 10
Cladding support strategy using vertical furring through rigid insulation boards

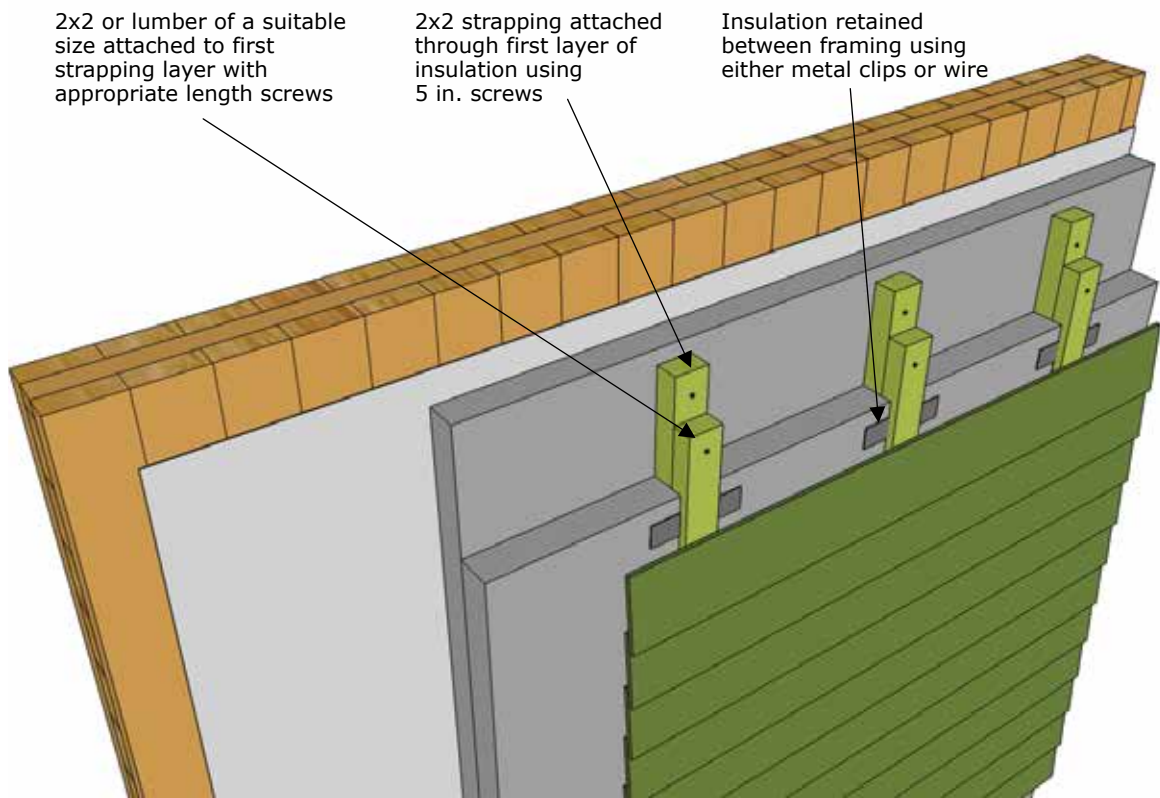
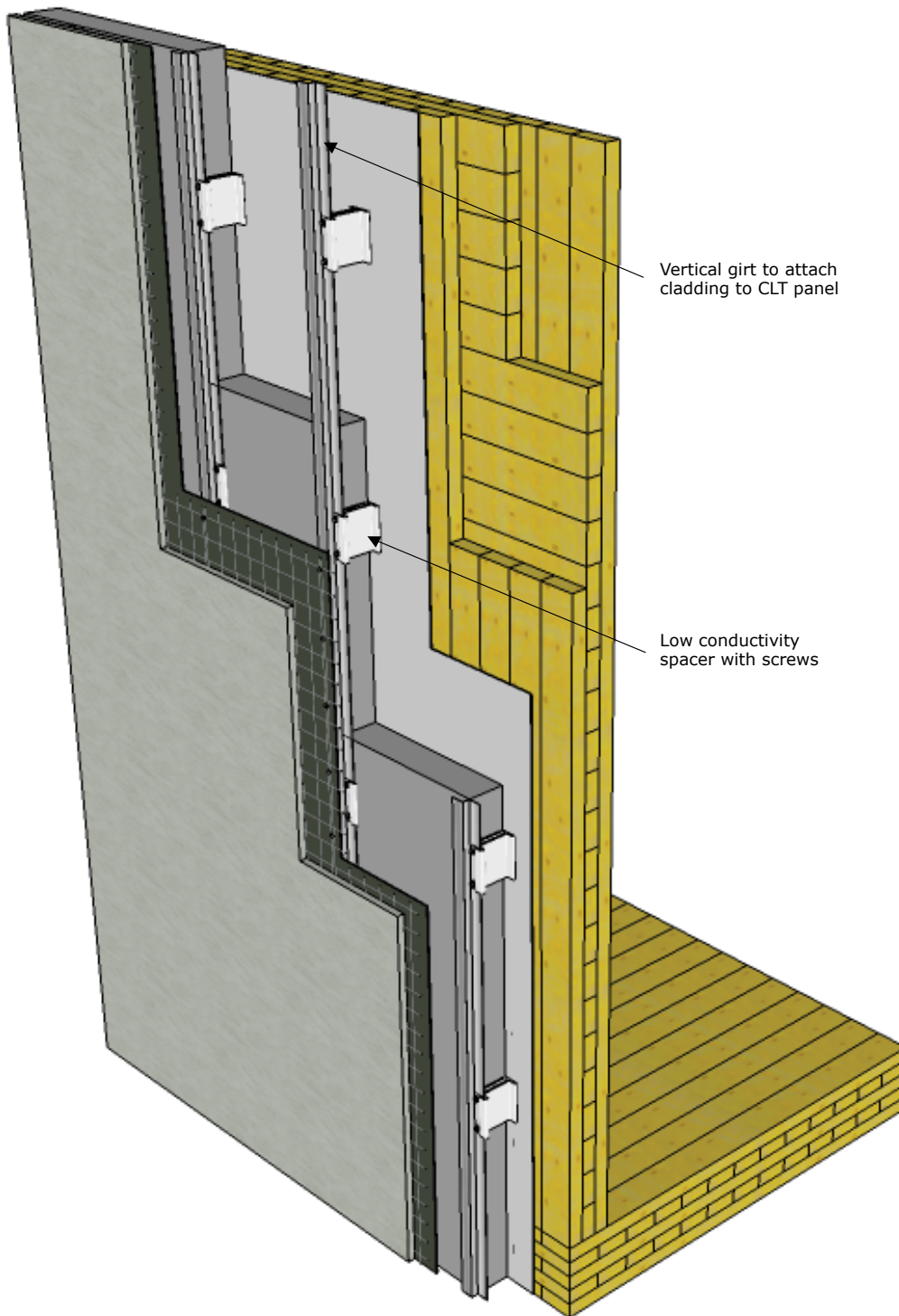


Figure 11

Cladding support strategy using two layers of rigid insulation and two strapping members: this configuration allows for the use of shorter screws and greater insulation thicknesses, while minimizing thermal bridging



Vertical girt to attach cladding to CLT panel

Low conductivity spacer with screws

Figure 12

Cladding support strategy using low conductivity spacers with screws providing rigid support to hang exterior vertical girt and cladding (used with permission of FPIinnovations, RDH Building Engineering, and other partners)

3.1.1 Detailing Installation of Windows and Doors

The installation of windows in a CLT wall assembly must follow basic water management principles as well as conform to window manufacturer instructions and consensus standards such as ASTM E2112 (2007a). When installing a window into an exterior insulated assembly, several window installation techniques are possible depending on the placement of the window frame. Placing the exterior side of the window frame in the same plane as the WRB on the exterior of the CLT panel is recommended.

A general schematic of a window installation is provided in Figure 9. In addition, Figure 13 depicts a cross section of the detailing at the window sill. A sloped metal sill flashing below the window directs water running off the window to the exterior of the cladding. Below the window, a sloped wood sill is placed over the CLT rough opening. This sill is covered with a self-adhered flashing that overlaps the WRB shingle fashion below the rough opening. A second piece of self-adhered flashing covers the first piece and laps over the exterior insulation. Both of these flashings have upturned end dams to ensure that the sill-jam intersections are protected. Key points to consider when detailing include:

- Air barrier continuity must be maintained from the WRB at the CLT surface, through the rough opening and to the window frame;
- The membrane used at the window sill should be resistant to standing water and vapor impermeable. All other membranes should preferably be vapor permeable to prevent water from being trapped within the CLT panel;
- Water should not be drained behind the insulation/WRB interface below a window or other penetration. Water should be drained to the exterior of the insulation or directly to the exterior where possible.

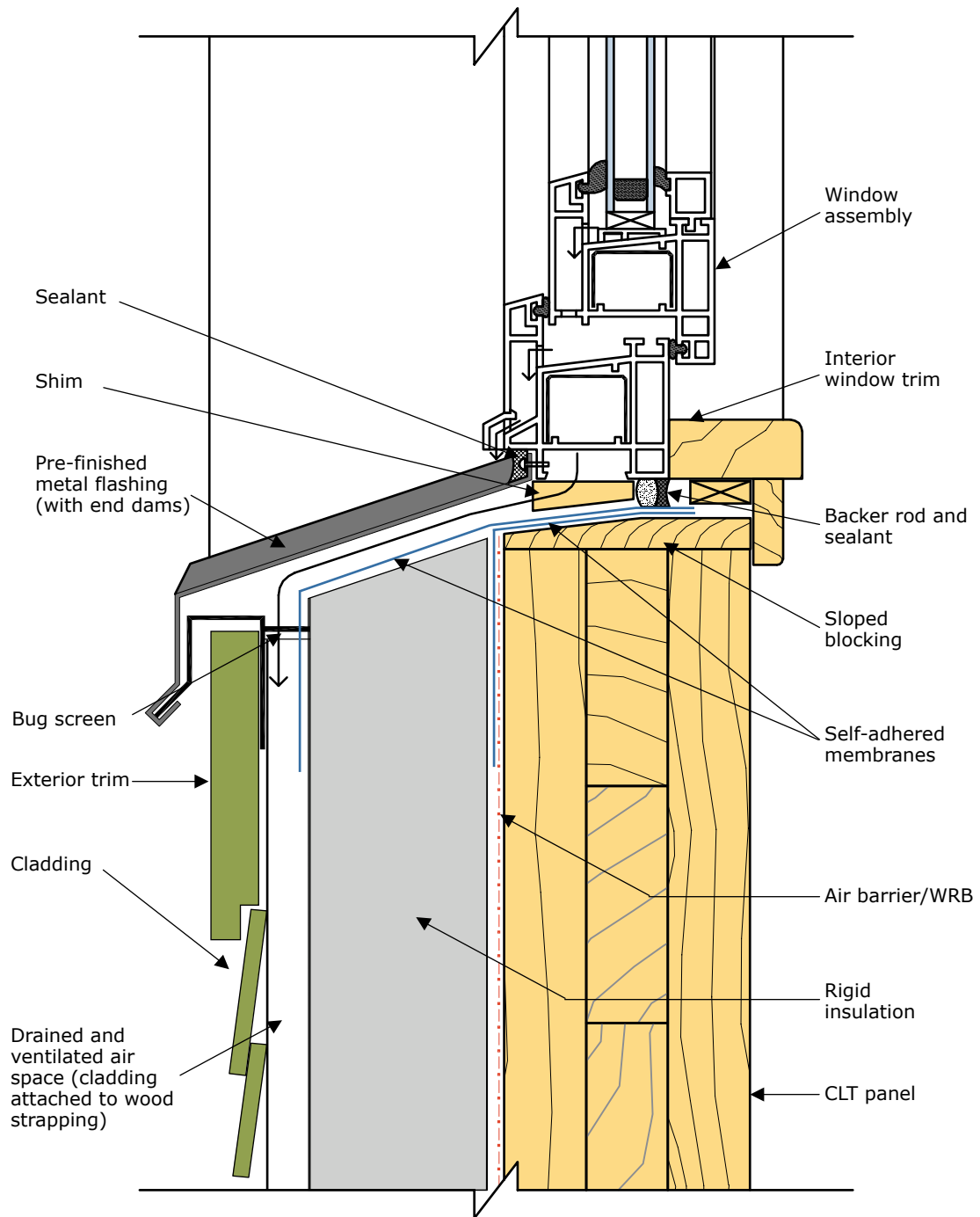


Figure 13
Window installation schematic using sloped wood sill

3.1.2 Detailing Foundation/Wall Intersections and Considerations at Grade

CLT panels must be protected from moisture at grade. Typical wood-frame construction best practice regarding clearance between grade and wood should be followed: a minimum of 6 in. (150 mm) or local code required clearance should be maintained between the bottom of the CLT panel and the finished ground level after landscaping. The CLT panel should also be separated from the concrete using a waterproof membrane and a treated wood sill plate is recommended to prevent capillary water absorption through the end grain of vertical boards in the CLT (Figure 14). A sill gasket and sealant can be provided for air sealing.

As shown in Figure 14, the exterior insulated above-grade CLT wall assembly details easily into an exterior insulated below grade basement wall or slab footing. Flashing is provided at the base of the above grade CLT wall which can be profiled to cover the below grade insulation. This insulation (typically extruded polystyrene, XPS, or rigid mineral wool) is placed on the exterior of the concrete and should be placed up tight to the underside of the flashing. Since this can provide hidden access for termites, the XPS insulation should be borate-treated and the flashing should be installed in such a manner to act as a termite shield where this hazard exists. Other termite management measures may be required by local building codes as discussed below in Section 5.

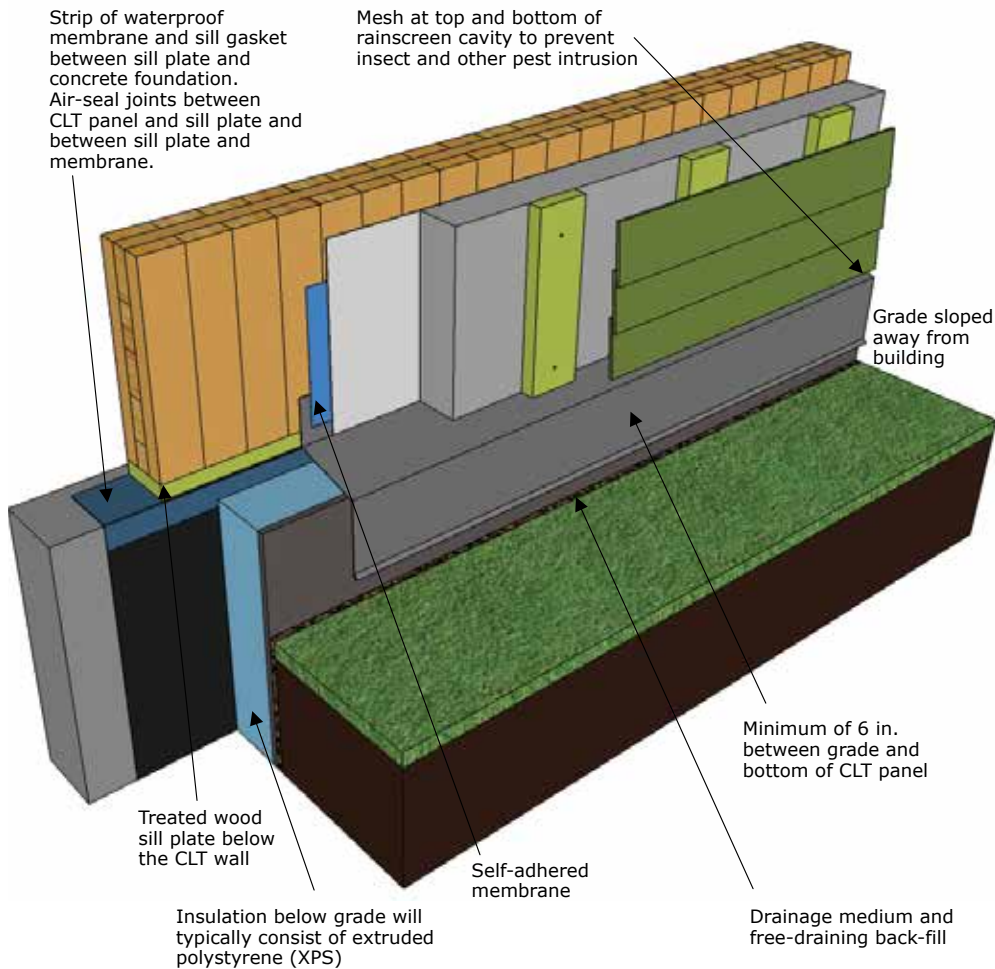


Figure 14
Schematic of CLT wall assembly and concrete foundation at grade

3.1.3 Balconies

Cantilevered balconies can be problematic in terms of durability and thermal performance in any type of structure. Cantilevered CLT balconies are not recommended because of the risk of water intrusion. Balconies historically had major moisture-related problems in wood-frame buildings when poorly-executed details allowed water intrusion into structures (Morrison Hershfield Ltd., 1998). A balcony, from the perspective of water management detailing, is equivalent to a low-slope roof that intersects an exterior wall. Proper detailing would require a waterproof membrane properly lapped into the wall's drainage plane and positive drainage of the balcony away from the balcony/wall intersection, so that water is not directed back into the building and does not pond on the membrane. CLT is typically made with lumber that is not preservative-treated, and most of the wood species used for CLT are vulnerable to decay if they get wet and remain wet for an extended period (moisture content exceeding ~26%). If decay were to occur in the deck of a cantilevered CLT balcony, there would be great difficulty and cost involved in repairing the structure, because the CLT panel that served as the balcony deck would be the same panel that served as the structural floor inside the building.

If the building will have balconies, the best approach for a CLT structure is to offset the balcony from the exterior wall. For all but the driest of climates, it would be preferable to construct a wood-frame balcony using pressure-treated lumber rather than CLT. There are a number of ways to keep the balcony thermally isolated from the building—connecting the balcony structure to the CLT structure intermittently through the exterior insulation, combining offset point supports with tie rods, or providing the balcony with its own structural frame and foundation. Water proofing membranes typically require a positive slope of at least 2% (¼ in. per foot or 20 mm per meter). The designer must also consider wood shrinkage and other potential movement. See other references for connections and water management detailing (Lstiburek, 2007, 2011; Smith, 2007; HPO, 2011; Straube, 2012).

3.2 Roof Assemblies

Effective water management starts with thoughtful design that deflects and drains water from the roof, walls, and foundation away from the building. Directing water from the roof away from the enclosure reduces the moisture load on walls and foundations.

3.2.1 Water Managed Roof Design Tips

- Create designs that do not trap or channel water into the building;
- Avoid roof designs with horizontal valleys that trap water;
- Avoid roof designs that slope into vertical walls;
- Always use seamless kick-out flashings at roof/wall intersections. Such flashings should be properly integrated with the WRB. A self-adhered flashing is recommended from the kick-out and step flashing onto the CLT wall. This will deflect any water that gets behind the WRB onto the flashing to the exterior;
- Remember that floor plans dictate roof plans and roof drainage paths. Every jog in the floor plan typically telegraphs to a more complicated roof plan;
- Keeping the roof design simple reduces complex framing and minimizes flashing errors;
- Gutters and downspouts should direct water to a drain or to the ground (away from the building) rather than onto a lower-pitched roof or slab.

3.2.2 Sloped Roofs

CLT panels can be effectively used for roof panels. CLT roof panels can provide more interior volume, which can become an aesthetically appealing design element if the fire codes allow the panels to be exposed to the interior. The thickness of CLT roof panels is based on loads, structural supports, design and span of the panels. A variety of roofing material approaches can work with CLT as long as thoughtful attention is paid to design details for insulation and moisture management. Water management strategies for roofs are similar to the design considerations for walls—deflection, drainage, drying, and durable materials (Section 2.2.2). In a one inch rain, roofs are exposed to and must deflect 640 gallons per 1000 square feet of roof area.

Energy codes dictate higher R-value insulation requirements for roofs than walls. A common design is to have the insulation, moisture control layer and air barrier placed on the exterior side of the panel, similar to the CLT wall assemblies presented above. Rigid insulation⁴, with a plywood or OSB nail base for attaching roofing materials, may provide a slimmer roof profile that can make for easier interfacing of insulation, roof flashings, and trim components. Figures 15 and 16 show material sequencing of a sloped CLT roof and tie-in details to a CLT wall assembly at the underside.

Since bulk water deflection is a primary requirement for roofs, a vapor impermeable, self-adhered membrane is applied over the plywood or OSB sheathing as a secondary water control underlayment. Prior to installation of the rigid insulation, plywood or OSB sheathing, and self-adhered membrane, the CLT roof panels should be covered with a water-resistive material such as roofing felt. Roof assemblies generally have greater insulation levels than walls, and drying is facilitated to the inside through the CLT panel with a vapor permeable interior finish.

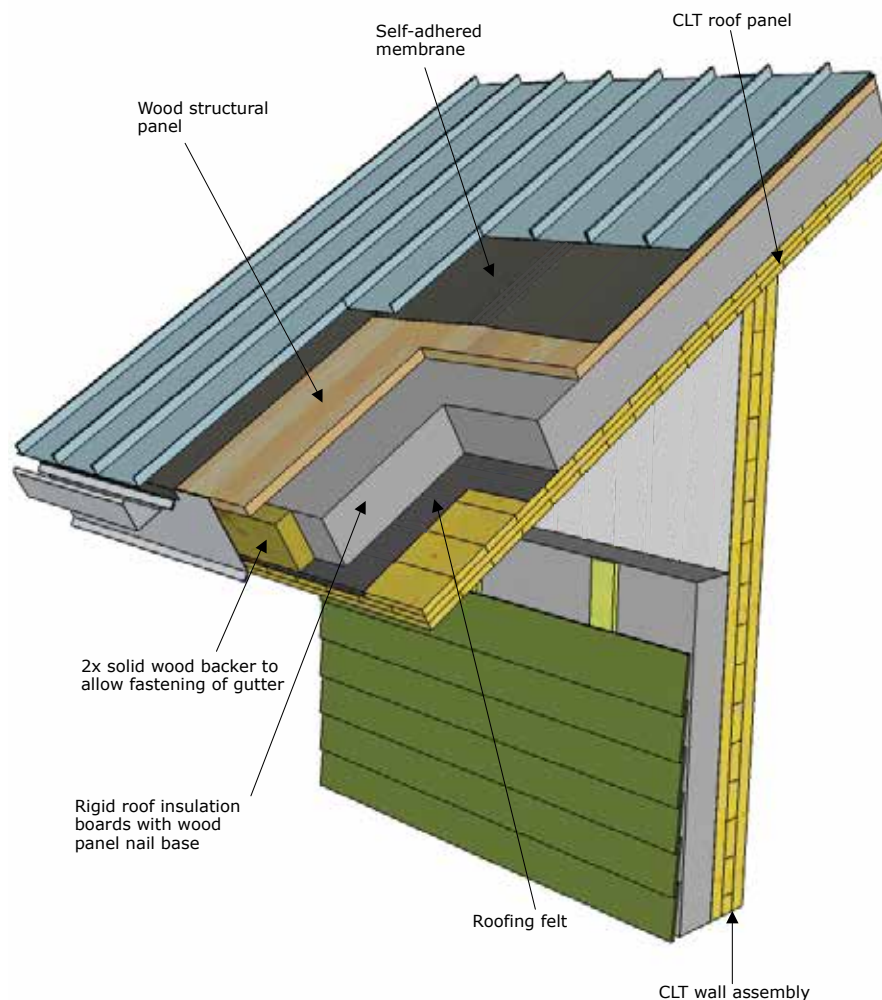


Figure 15

Top view of a sloped CLT roof assembly showing material sequencing and transition to a CLT exterior wall with exterior insulation and ventilated cladding (certain roofing materials may require a vented air space between the roofing and the membrane, which can be created using purlins or other methods)

⁴If rigid foam insulation is incorporated in CLT construction, the fire code provisions pertaining to foam plastic insulation will need to be addressed (see Chapter 8 of the CLT Handbook).

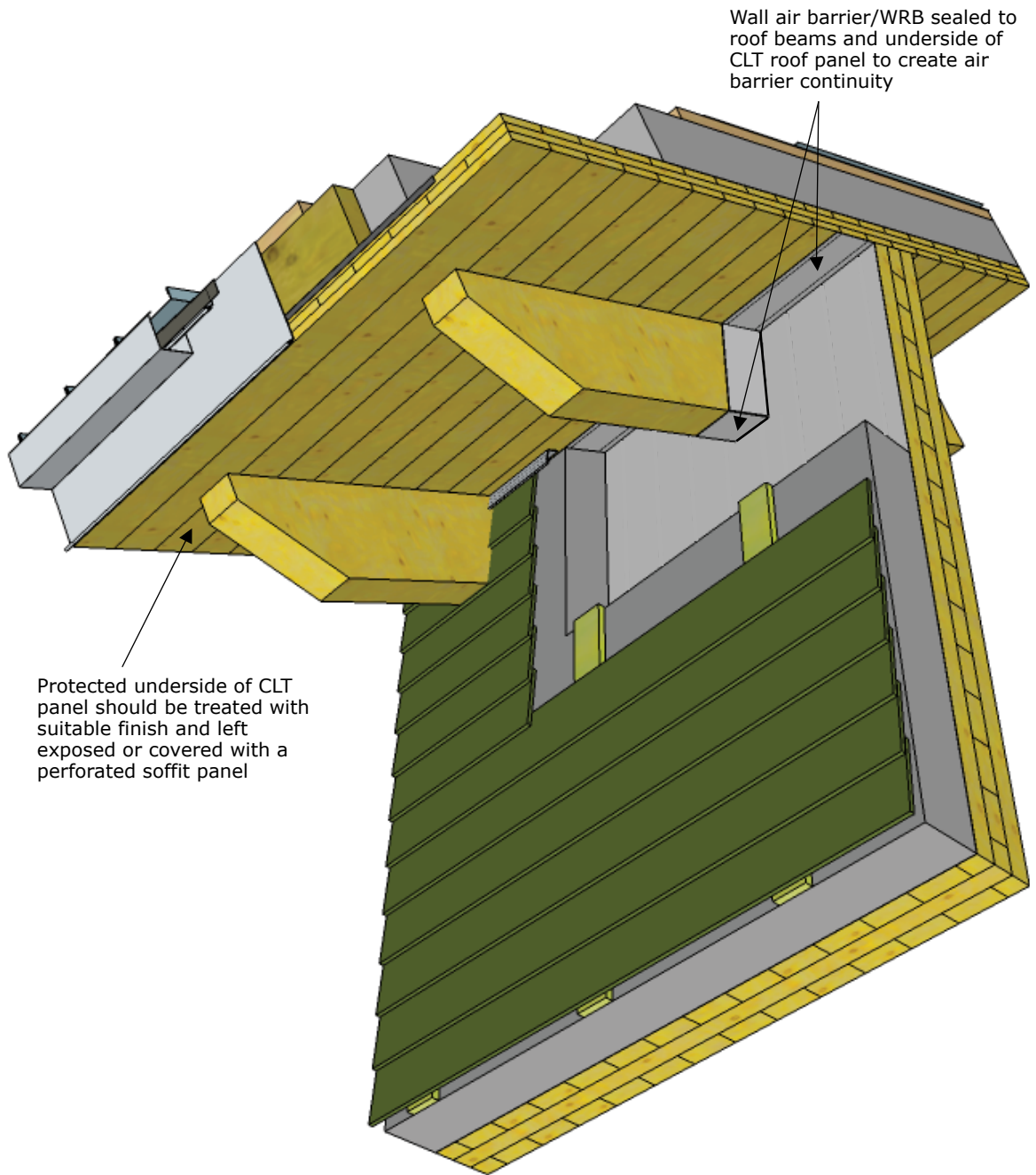


Figure 16

Bottom view of a sloped CLT roof assembly showing material sequencing and transition to a CLT exterior wall with exterior insulation and ventilated cladding

3.2.3 Low-slope Roof Decks and Parapets

Low-slope roof assemblies for CLT construction have design requirements for water management similar to sloped roofs. Protection of CLT roof panels during construction is most critical (Section 4). Conventional flat roofing systems can be applied for use with CLT roof construction. It is crucial that underlayment membranes be redundant and carefully interfaced with parapet wall flashing to provide proper shingling, and deflection of water away from roof-wall intersections and penetrations. Rigid insulation joints should be staggered and sealed to reduce airflow and prevent water penetration.⁵ Figure 17 shows material sequencing of a low-slope CLT roof and tie-in details to a CLT wall assembly.

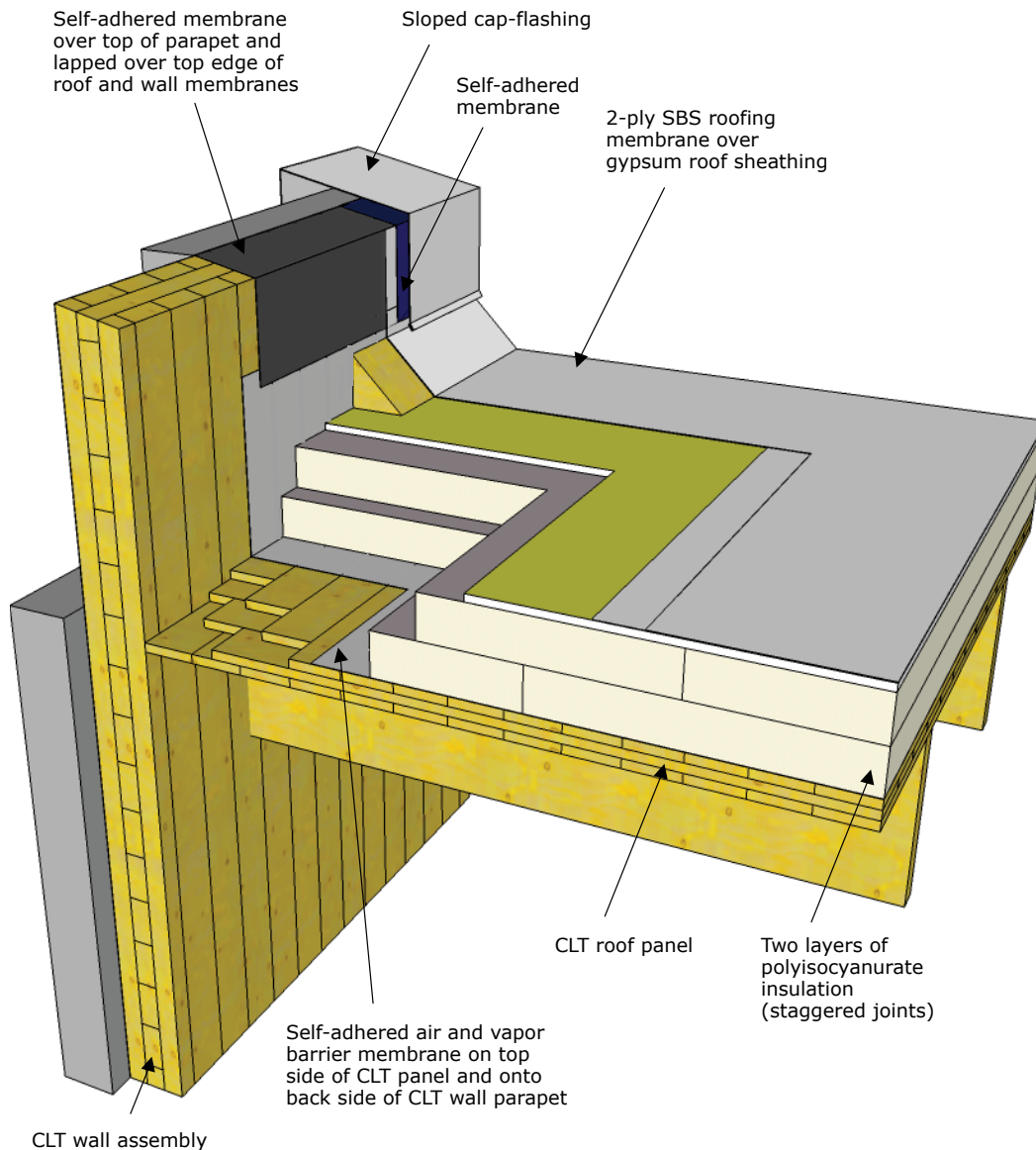


Figure 17

Low-slope CLT roof detail showing material sequencing of a conventional roofing assembly with tie-in to CLT parapet wall (slope to drains is achieved either by sloping the roof deck or by tapering the rigid insulation)

⁵If rigid foam insulation is incorporated in CLT construction, the fire code provisions pertaining to foam plastic insulation will need to be addressed (see Chapter 8 of the CLT Handbook).

Another option for low-slope roofs is the application of high density (approx. 3 lb. \cdot ft.⁻³) closed-cell spray polyurethane foam (ccSPF) insulation with a polymeric topcoating. This type of insulation can be sprayed directly over a membrane on the CLT. It absorbs a negligible amount of water, is air impermeable, and is vapor semi-impermeable at 2 in. (50 mm) or greater thickness. A polymeric top coat over the ccSPF can provide mechanical and UV protection and must be properly maintained. When applied as a roofing substrate, ccSPF insulation practically eliminates thermal bridging and provides air sealing at parapet walls, curbs, and other roofing penetrations. Gravel-surfaced systems and single-ply membrane technology (i.e., fully adhered fleece-backed membranes, loose-laid ballasted) can also be used with ccSPF roof systems.

4

CONTROL OF MOISTURE DURING CONSTRUCTION

CLT panels, similar to other wood products, should always be protected from exposure to rain, snow, and wet ground during transport, jobsite storage, and construction process (see also Chapter 12). CLT panels are vulnerable to damage from excessive wetting due to the nature of their laminated construction and because they may absorb large quantities of water through the faces, exposed end grain, and gaps between the panel laminations. Recall that liquid water absorption is much more rapid at end grain surfaces. Applying water repellents to end grain of CLT panels may effectively retard water absorption; however, film-forming coatings may retard drying.

CLT panels are much more massive than standard dimension lumber and structural panels such as plywood and OSB. The mass and thickness of CLT means that these panels will likely take longer to dry out if allowed to become wet. In addition, cyclic wetting and drying can cause wood expansion and contraction, which may damage the laminations and lead to distortion of the panels. Therefore, prevention of wetting should be a priority in construction.

Wetting of CLT panels during construction can be minimized by paying careful attention to weather and construction schedules, delivering the product just on time, minimizing construction time, and protecting CLT panels from wetting once they are installed. Temporary protection can be attached in the manufacturing facility and should be maintained while stored on site. This protection should also be maintained as the panels are erected in place in order to protect them until the roof or other elements, such as the WRB, provide adequate protection.

CLT exterior walls should be protected as soon as possible with a WRB. A vapor permeable WRB is desirable to allow the wood to dry while preventing further water absorption. CLT roof panels should likewise be protected as soon as possible with a waterproof membrane, preferably while the panels are dry. Applying an impermeable membrane over CLT panels that are already wet is problematic for two reasons. First, drying of the CLT will be impeded. Second, the membrane may not adhere well to wet wood. If roof panels are wetted before the protective membrane is applied, it may be necessary to provide temporary shelter above the roof and to dry the panels.

Even with these precautions, it is likely that CLT panels will experience some wetting during transport or construction, and be installed with built-in moisture in localized areas. Therefore, the most durable wall design strategies will use vapor permeable materials to allow for excess moisture to escape from the assembly, thereby preventing any damage and deterioration. In cases where exterior materials with low vapor permeance are selected, the CLT panels should be dry prior to their installation.

5

WOOD PRESERVATIVE TREATMENT FOR INCREASED DURABILITY

CLT panels, especially any exposed portions and parts in direct contact with foundations less than 6 in. (150 mm) above finished ground level, would benefit from wood preservative treatment, particularly in wetter or more humid climates or where termites are prevalent. While best practice construction and design strategies attempt to minimize exposure of the wood panels to wetting, some CLT panels will inevitably be exposed to moisture during their lifetime and the additional factor of safety provided by wood preservatives can be beneficial to the durability of the buildings.

In terms of treatment, the water-borne preservatives used for treatment of lamina prior to manufacture of glulam posts and beams can generally be applied to lumber destined for manufacture of CLT. Manufacturers should ensure that the preservatives used do not adversely affect glue bonds or that resin modifiers are added as needed. This approach could be applied to the entire CLT panel or to parts of the panel anticipated to be exposed to conditions conducive to decay. Conventional pressure treatment with waterborne preservatives post manufacture would likely cause excessive distortion of CLT panels. New processes are available using low uptake spray, dip or very brief pressure treatments followed by conditioned storage to facilitate further penetration. These may prove suitable for CLT. Non-swelling oil-based treatments used for industrial glulam post manufacture are not a preferred approach for CLT buildings due to VOC emissions; most are not registered for interior use. Non-penetrating surface treatments are not likely to be effective against decay or termites but may be effective against surface mold. Where moisture ingress will be highly localized and predictable, boron or boron/copper rods can be used for local protection. In most cases, boron rods should be used in combination with a borate/glycol surface treatment and a film-forming coating to prevent leaching.

Subterranean and drywood termites would be much more difficult to eradicate from CLT panels than from platform frame construction. In areas with a high native termite hazard plus the Formosan subterranean termite, multiple lines of defense should be implemented to prevent termite damage to CLT panels and other wood or cellulose-based building components. The use of termite soil barriers such as termiticide soil treatment, and slab and foundation detailing to prevent termite intrusion should be taken into consideration during design. Preservative treated wood is also recommended in these areas for CLT panels and other wood components. Site management measures should eliminate nests and termite food sources such as stumps, formwork and other untreated wood in the soil. In addition, termite control measures should also be provided to below grade insulation materials such as XPS. Regular surveillance is also recommended to detect and treat termite infestation before it gets well established.

The use of fire retardants may help meet fire safety requirements and warrant the use of exposed CLT panels for aesthetic purposes. Some fire retardants contain boron and will also provide decay and termite resistance.

6

CONCLUDING COMMENTS

This Chapter provides guidance to assist practitioners in designing building enclosures with CLT panels that are suited to U.S. conditions. The Chapter emphasizes heat, air, and moisture control strategies and details for durability, energy performance, indoor air quality, and occupant comfort. The overarching strategies are to prevent wetting of CLT panels by drained wall systems, to control airflow using an air barrier to the exterior of the CLT panels, to place rigid insulation to the exterior of the panels, to prevent moisture from accumulating within the panels, and to allow the panels to dry should they get wet. In certain climates, preservative treatment of CLT is recommended to provide additional protection against potential hazards such as decay and termites. However, these guidelines are not intended to substitute for the input of a professional building scientist. This may be required in some jurisdictions and is recommended in all areas at least until such time as CLT construction becomes common practice.

7

REFERENCES

- AF&PA. 2005. *National design specification (NDS) for wood construction*. ANSI/AF&PA NDS-2005. Washington, DC: American Forest & Paper Association. American Wood Council. 174 p.
- APA. 2011. *Standard for performance-rated cross-laminated timber*. ANSI/APA PRG 320-2011. Tacoma, WA: APA – The Engineered Wood Association.
- ASHRAE. 2007. *Energy standard for buildings except low-rise residential buildings*. ANSI/ASHRAE/IESNA Standard 90.1-2007. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- _____. 2009. *ASHRAE handbook - Fundamentals*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- ASTM. 2005. *Standard test methods for water vapor transmission of materials*. ASTM E96 / E96M – 05. West Conshohocken, PA: ASTM International.
- _____. 2007a. *Standard practice for installation of exterior windows, doors and skylights*. ASTM E2112 – 07. West Conshohocken, PA: ASTM International.
- _____. 2007b. *Standard test methods for specific gravity of wood and wood-based materials*. ASTM D2395-07ae1. West Conshohocken, PA: ASTM International.
- _____. 2009. *Standard test method for airflow resistance of acoustical materials*. ASTM C522-03(2009)e1. West Conshohocken, PA: ASTM International.
- Baker, P. 2012. *External insulation of masonry walls and wood framed walls*. Research Report 1204. Somerville, MA: Building Science Corporation.
- Breyer, D., K. Fridley, K. Cobeen, and J.D. Pollock. 2006. *Design of wood structures*. 6th ed. New York: McGraw-Hill Professional.
- Brock, L. 2005. *Designing the exterior wall: An architectural guide to the vertical envelope*. Hoboken, NJ: John Wiley & Sons.
- BSC. 2007. *Guide to insulating sheathing*. Westford, MA: Building Science Corporation.
- Burnett, E., J. Straube, and A. Karagiozis. 2004. *Synthesis report and guidelines*. Report 12 of *Development of design strategies for rainscreen and sheathing membrane performance in wood frame walls*. ASHRAE Research Project 1091. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

- Carll, C., and T.L. Highley. 1999. Decay of wood and wood-based products above ground in buildings. *Journal of Testing and Evaluation* 27 (2):150-158.
- Carll, C., and A.C. Wiedenhoef. 2009. Moisture-related properties of wood and the effects of moisture on wood and wood products. In *Moisture control in buildings: The key factor in mold preventions*, edited by H.R. Trechsel and M.T. Bomberg. 2nd ed. Chapter 4, p. 54-79. West Conshohocken, PA: ASTM International.
- Carmeliet, J., H. Hens, and G. Vermeir, eds. 2003. *Research in building physics: Proceedings of the 2nd International Conference on Building Physics, 14-18 September 2003, Antwerpen, Belgium*. Exton, PA: A.A. Balkema Publishers.
- CCHRC. 2009. *REMOTE: A manual*. Fairbanks, AK: Cold Climate Housing Research Center, 42 p. http://cchrc.org/docs/best_practices/REMOTE_Manual.pdf (accessed November 26, 2012).
- CertiWood™. 2012. *Plywood design fundamentals*. North Vancouver, BC: CertiWood™ Technical Centre. http://www.canply.org/pdf/main/plywood_designfund.pdf (accessed June 30, 2012).
- CSA. 2009. *Engineering design in wood*. CAN/CSA O86-09. Toronto, ON: Canadian Standards Association.
- CWC. 2005. *Introduction to wood design*. Ottawa, ON: Canadian Wood Council. 400 p.
- Derome, D. 2010. *The nature, significance and control of solar-driven diffusion in wall systems*. ASHRAE Research Project 1235. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- Finch, G., and J. Straube. 2007. Ventilated wall claddings: Review, field performance, and hygrothermal modeling. In *Proceedings, Thermal Performance of the Exterior Envelopes of Whole Buildings X International Conference, December 2-7, 2007, Clearwater Beach, Florida*. Paper 51. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- Gagnon, S., and C. Pirvu, eds. 2011. *CLT handbook: Cross-laminated timber*. Canadian ed. Special Publication SP-528E. Quebec, QC: FPInnovations. 1 v.
- Gereke, T., P.J. Gustafsson, K. Persson, and P. Niemz. 2009. Experimental and numerical determination of the hygroscopic warping of cross-laminated solid wood panels. *Holzforschung* 63(2009):340-347.
- Goto, Y., K. Ghazi Wakili, Y. Ostermeyer, Th. Frank, N. Ando, and H. Wallbaum. 2011. Preliminary investigation of a vapor-open envelope tailored for subtropical climate. *Building and Environment*. 46(2011):719-828.
- Hazleden, D.G., and P.I. Morris. 1999. Designing for durable wood construction: the 4 Ds. In *Proceedings, 8th International Conference on Durability of Building Materials and Components*, Lacasse, M.A and Vanier, D.J., eds. 1:734-745. Ottawa, ON: NRC Research Press.
- Hazleden, D.G., and P.I. Morris. 2001. The influence of design on drying of wood-frame walls under controlled conditions. In *Proceedings, Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes*, Clearwater Beach, Florida. Paper 70. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- HPO. 2011. *Building enclosure design guide: Wood-frame multi-unit residential buildings*. Vancouver, BC: BC Housing, Homeowner Protection Office.
- ICC. 2009. *International energy conservation code*. Washington, DC: International Code Council.
- ISO. 2002. *Hygrothermal performance of building materials and products-determination of water absorption coefficient by partial immersion*. ISO 15148:2002. Geneva, Switzerland: International Organization for Standardization.

- Kumaran, M.K., J.C. Lackey, N. Normandin, F. Tariku, and D. van Reenen. 2002. *A thermal and moisture transport database for common building and insulating materials*. ASHRAE Research Project RP-1018. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- Lepage, R. 2012. Moisture responses of wall assemblies of cross-laminated timber construction in cold climates. M.A.Sc. Thesis, Civil Eng. Dept., University of Waterloo, ON.
- Lstiburek, J. 2006a. *Understanding air barriers*. Building Science Digests, BSD-104. Somerville, MA: Building Science Corporation.
- _____. 2006b. *Understanding vapor barriers*. Building Science Digests, BSD-106. Somerville, MA: Building Science Corporation.
- _____. 2006c. *Water management guide*. Westford, MA: Building Science Press.
- _____. 2007. A bridge too far: Thermal bridges—Steel studs, structural frames, relieving angles and balconies. *ASHRAE Journal* 49(10): 64-68.
- _____. 2010a. *Mind the gap, eh!* Building Science Insight, BSI-038. Somerville, MA: Building Science Corporation.
- _____. 2010b. *The perfect wall*. Building Science Insight, BSI-001. Somerville, MA: Building Science Corporation.
- _____. 2011. Decks: Roofs you can walk on. *ASHRAE Journal* 53(3):62-68.
- Lstiburek, J., and J. Carmody. 1994. *Moisture control handbook: Principles and practices for residential and small commercial buildings*. New York: John Wiley & Sons.
- McClung, R., J. Straube, H. Ge, and J. Wang. 2012. Field study of hygrothermal performance of cross-laminated timber wall assemblies with built-in moisture. In *Proceedings of the 5th International Building Physics Conference, May 28th to 31st, 2012, Kyoto*. 361-368.
- Morris, P.I. 1998. Understanding biodeterioration of wood in structures. Report to British Columbia Building Envelope Council. Vancouver, BC: Forintek. 23 p.
- Morrison Hershfield Ltd. 1998. *Survey of building envelope failures in the coastal climate of British Columbia*. Technical Series 98–102. Ottawa: Canada Mortgage and Housing Corporation. 56 p.
- NIST. 2010. *American softwood lumber standard*. Voluntary Product Standard PS 20-10. Gaithersburg, MD: National Institute of Standards and Technology.
- NRC. 2012. Characterization of hygrothermal properties of CLT. Report to FPInnovations. Ottawa, ON: National Research Council of Canada.
- Rose, W.B. 2005. *Water in buildings: An architect's guide to moisture and mold*. Hoboken, NJ: John Wiley & Sons.
- Siau, J.F. 1984. *Transport processes in wood*. New York: Springer-Verlag. 245 p.
- Skaar, C. 1988. *Wood-water relations*. New York: Springer-Verlag. 283 p.

- Skogstad, H.B., L. Gullbrekken, and K. Nore. 2012. *Air leakages through cross laminated timber (CLT) constructions*. Oslo, Norway: Norwegian Institute of Wood Technology (Treteknisk). http://www.treteknisk.com/Air_leakages_in_cross_laminated_timber_constructions_28022011_docx_xy7tg.pdf (accessed June 30, 2012).
- Smith, A. 2007. Repairing cantilevered balconies. In *The JLC guide to moisture control: Practical details for durable buildings*, 239-243. Williston, VT: Hanley Wood.
- Stamm, A.J. 1964. *Wood and cellulose science*. New York: Ronald Press, 549 p.
- Straube, J. 2012. *High performance enclosures: Design guide for institutional, commercial, and industrial buildings in cold climates*. Somerville, MA: Building Science Press.
- Straube, J., and E. Burnett. 2005. *Building science for building enclosures*. Westford, MA: Building Science Press.
- Straube, J., and J. Smegal. 2007. The role of small drainage gaps behind wall claddings on drainage and drying. In *Proceedings, 11th Canadian Conference on Building Science and Technology, Banff, Alberta, Canada*.
- TenWolde, A., J.D. McNatt, and L. Krahn. 1988. *Thermal properties of wood and wood panel products for use in buildings*. ORNL/Sub/87-21697/1. Oak Ridge, TN: Oak Ridge National Laboratory. 38 p.
- Thompson, A., and B.N. Taylor. 2008. *Guide for the use of the International System of Units (SI)*. NIST Special Publication 811. Gaithersburg, MD: National Institute of Standards and Technology.
- Trechsel, H.R., and M.T. Bomberg, eds. 2009. *Moisture control in buildings: The key factor in mold prevention*. 2nd ed. West Conshohocken, PA: ASTM International.
- USDA. 2010a. Biodeterioration of wood. In *Wood handbook: Wood as an engineering material*. Gen. Tech. Rep. FPL-GTR-113. Chapter 14. Madison, WI: U.S. Department of Agriculture. Forest Service. Forest Products Laboratory.
- _____. 2010b. Moisture relations and physical properties. In *Wood handbook: Wood as an engineering material*. Gen. Tech. Rep. FPL-GTR-113. Chapter 4. Madison, WI: U.S. Department of Agriculture. Forest Service. Forest Products Laboratory.
- Wang, J., J. Clark, P. Symons, and P.I. Morris. 2010. Time to initiation of decay in plywood, OSB and solid wood under critical moisture conditions. In vol. 2 of *Proceedings of the International Conference on Building Envelope Systems and Technologies (ICBEST 2010)*, edited by A. Baskaran. Ottawa, ON: National Research Council of Canada. Institute for Research in Construction.
- Wang, J., and P.I. Morris. 2010. *A review on conditions on decay initiation and progression*. International Research Group on Wood Protection, Document No. IRG/WP/10-20444. Stockholm, Sweden: IRG. 10 p.
- Wang, J., M. Phalguni, and P.I. Morris. 2012. Sorption and capillary condensation in wood and the moisture content of red pine at high relative humidity. *Journal of Building Physics*. Published online, doi: 10.1177/1744259112453829.



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