Taller and Larger Wood Buildings:

Potential Impacts of Wetting on Performance of Mass Timber Buildings

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SUMMARY

This report summarizes basic wood-moisture relationships, and reviews conditions conducive to adverse consequences of wetting, such as staining, mold growth, decay, strength reduction, and dimensional change and distortion. It also outlines solutions and available resources related to on-site moisture management and design measures. Sorption, including desorption (i.e., loss of moisture) and adsorption (i.e., gain of moisture), is the interaction of wood with the water vapour in the ambient environment. The consequent changes in the amount of bound moisture (or “hygroscopic moisture”) of pre-dried wood affect the physical and mechanical properties. However, the core of a mass timber responds slowly and is well protected from fluctuations in the service environment. Mold growth and fungal staining may occur in a damp environment with a high relative humidity or sources of liquid water. Sorption alone does not increase the moisture content (MC) of pre-dried wood above the fibre saturation point and does not lead to decay. Wood changes its MC more quickly when it absorbs liquid water compared with sorption. This introduces free water (or “capillary water”) and increases the MC above the fiber saturation point. Research has shown that decay does not start below a MC of 26%, when all other conditions are favourable for fungal growth. Decay can cause significant strength reduction, for toughness and impact bending in particular. For a wood member in service, the effect of decay is very complicated and depends on factors, such as the size of a member, loading condition, fungi involved, location and intensity of the attack. Appearance of decay does not reflect true residual stiffness or strength. For wood-based composites severe wetting without decay may affect the structural properties and performance due to damage to the bonding provided by the adhesive inside.

There are large variations among wood species, products and assemblies in their tendency to trap moisture and maintain durability. For a given wood species, the longitudinal direction (vs. the transverse directions) and the sapwood (vs. heartwood) absorb water more quickly. Capillaries between unglued joints (e.g., some CLT, glulam), exposed end grains, and interconnected voids inside a product increase the likelihoods of moisture entrapment, slow drying, and consequently decay. Many mass timber products, composites in particular, may be modified to reduce these issues. Measures should also be taken in design, during construction, or building operation to reduce the moisture risk and increase the drying ability. It is also important to facilitate detection of water leaks in a mass timber building and to make it easier to repair and replace members in case damage occurs. Preservative-treated or naturally durable wood should be used for applications that are subjected to high moisture risk. Localized on-site treatment may be appropriate for specific vulnerable locations. Changing environmental conditions may cause issues, such as checking, although it does not compromise the structural integrity in most cases. Measures may be taken to allow the timbers to adjust to the service conditions slowly (e.g., through humidity control), particularly in the first year of service.

Overall there is very little information about the potential impacts that various wetting scenarios during construction and in service could realistically have on mass timber products and systems. The wetting and drying behaviour, impacts of wetting and biological attack on the structural capacity, and the behaviour under extreme environmental conditions, such as the very dry service environment that occurs during the winter in a northern continent, should be assessed to improve design of mass timber buildings.

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1 OBJECTIVES

- To identify potential impacts of wetting that may occur at different stages from construction to service on the performance of mass timber buildings
- To summarize solutions and resources available for managing moisture from construction to service
- To identify knowledge gaps for future research

2 INTRODUCTION

There is no reason a wood structure cannot last to meet the expectations for service life of modern buildings, with good protection provided against decay, insect attack, and fire during construction and in service. Many historical timber buildings exist in different parts of the world, with the oldest in Europe and Asia dating back to over 1000 years. In history one of the most important milestones for reducing decay potential was to use stone or brick footings, replacing wood in direct contact with the ground. In large cities of North America, many heavy timber frame buildings, built in the late 1800's or early 1900's and typically from 3 to 9 storeys, are still serving modern society (Koo 2013). In terms of modern light framing construction, numerous wood houses in North America are a few hundred years old. Wood bridges, albeit typically having higher exposure to the weather than the structural members of a building, can also last long when properly designed and built (Morris 2015a). The oldest are covered bridges with a roof to provide protection for the bridge below. In Southeast China, numerous covered bridges are about 1000 years old. In North America, one of the oldest covered bridges, Hyde Hall bridge located in Springfield, New York, was built in 1825 (Covered Bridge Society 2015).

For a modern building, normally there is no requirement for exceptional longevity. The National Building Code of Canada (NRC 2010) uses a return period of 50 years for design loads, such as wind, seismic, snow, and rain. This was increased from the return period of 30 years in the 2005 edition to more closely match the expected service life of a building. The Guideline on Durability in Buildings (CSA 2007) provides four categories of design service life, suggesting that most residential, commercial, and office buildings fall into the category of "Long life", which is defined to be from 50 to 99 years. A modern wood bridge is typically designed for a 75 year service life (CSA 2014). Wood is one of the best materials to meet such lifetime expectations. A demolition survey conducted in Minneapolis/St. Paul between 2000 and 2003 for a total of 227 buildings showed that the wood buildings last as long as or longer than the buildings made of other materials (O'Connor 2004). The survey indicated that there was no significant relationship between the structural system and the actual service life, with most non-residential buildings demolished in 50 years or less. The reasons for demolition were mostly related to factors, such as changed land values, changed needs of the building, or deterioration of mostly non-structural components due to lack of maintenance.

Most wood products and systems are in general quite resilient to moisture if kept within certain limits. However, as a bio-material, wood should be protected from wetting during construction and in service to avoid potential damage. Moisture affects the physical and mechanical properties of wood; but of more serious concern are potential durability issues, such as staining, mold growth, and decay. Moisture management during construction and in service has become particularly important for a modern building due to the overall reduced drying capacity of building envelope assemblies, resulting from increased insulation levels to meet the more stringent energy efficiency requirements, or the use of membrane or insulation products with low vapour permeance (Wang 2011). For a taller and larger building, the use of large-dimension built-up or composite wood members may also slow down drying (Wang 2014; Wang 2015a). Moreover, those buildings typically take longer to build, increasing the moisture absorption risk during construction, particularly in a wet climate. Moisture protection, especially at the construction site, was reported to be an urgent issue that deserves attention based on the experience with tall timber buildings in Europe (FII and BSLC 2014; Winter 2014).

This literature review provides a summary about basic wood-moisture relationships and conditions for potential consequences of wetting, such as staining, mold growth, decay, strength reduction, and dimensional issues. It then summarizes solutions and resources available related to on-site moisture management and design measures. In the context of mid-rise and taller wood buildings, this work attempted to focus on mass timber products and systems when possible. However, very limited information was found in literature. Light wood-frame systems were included when relevant information was available.

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4 WOOD AND MOISTURE BASICS

The amount of moisture is one of the important factors influencing wood properties and performance. This section covers basic relationship between wood and water, potential sources of moisture during construction and in building service, and the wetting and drying behaviour of wood.

4.1 Moisture in Wood

Wood cells are formed in an environment in the tree that always contains water. Wood has a natural affinity for water and always contains some moisture when used as a structural material. The moisture exists in wood either as bound water (or “hygroscopic water”) that is held within the cell walls or as free water (or “capillary water”) that is stored in the cell cavities. Moisture content (MC) is expressed as a percentage between the mass of water and the mass of oven-dry wood. As freshly cut (green) wood with a high MC dries, the free water evaporates first. Wood reaches the fibre saturation point when all of the free water is gone, leaving only the bound water within the cell walls. The fibre saturation point varies with species and measurement methods (Skaar 1988), but for most species it ranges from 25% to 30% (Panshin and De Zeeuw 1980). 30% is the most commonly referenced value as the fibre saturation point (FPL 2010, Chapter 4). The practical importance of this concept is it marks a turning point of a relationship curve between most physical (e.g., shrinkage, swelling) or mechanical (bending, compression, and tension) properties and MC. These properties change only with the change in the amount of bound water in cell walls.

Wood products have different MC specifications at the time of manufacture. In North America, structural dimension lumber (e.g., Spruce-Pine-Fir (S-P-F), Douglas Fir-Larch (D. Fir-L), Hem-Fir) is produced with the designation of either “S-Dry” (Surfaced Dry) or “S-Grn” (Surfaced Green). Lumber with designation of “S-Dry” means its MC is 19% or lower when it is planed or surfaced to the standard lumber dimension. Among “S-Dry”, “KD” (Kiln Dried) on a North American grade stamp indicates that the lumber has been kiln-dried to a MC of 19% or lower, typically targeting an average MC of 16%. “S-Grn” is not checked for MC at the time of surfacing but the MC is typically above 30%. “S-Grn” dimension lumber is not commonly used in large building projects these days. The MC of solid-sawn timbers is subject to the agreement between the contractor and the supplier. They are typically supplied “green” without kiln drying or air drying, with an average MC above 30%. When dimension lumber or timbers are preservative-treated, they typically have a high MC upon arrival at a construction site.

Engineered wood products are manufactured to have lower and more consistent MC than lumber and solid-sawn timbers. The manufacture has more strict moisture control requirements for achieving proper adhesive bonding to target a narrower range of strength properties. Laminated solid wood products, including glued-laminated timber (glulam) and cross-laminated timber (CLT), are manufactured at MC levels from 11% to 15%. Structural composite products (SCL), such as plywood, oriented strand board (OSB), parallel strand lumber (PSL), laminated strand lumber (LSL), oriented strand lumber (OSL), and laminated veneer lumber (LVL), are manufactured with MC levels lower than or close to the equilibrium moisture content (EMC) in service, typically from 6% to 12%. Engineered wood I-joists are typically made using kiln-dried lumber or SCL (e.g. LVL) for flanges and plywood or OSB for webs. Similarly, prefabricated frames, or closed assemblies including insulation, membranes, and other materials, usually have more control over wood MCs since they are built under sheltered or in conditioned environments. The wood typically has a MC below 15%; lower MCs, such as 12%, may be achieved when specified. See typical MC ranges at the time of manufacture in Appendix I.

However, it must be recognized that there is no assurance that the MC will not change after manufacture. Green or “S-Dry” products usually continue to lose moisture as they adapt to the environmental conditions, provided they are kept away from liquid water sources. Drier products, such as composite products, may gain moisture from the ambient environment when the humidity is high. Wood absorbs water to a greater degree when it is exposed to a source of liquid water. Such wetting is typically the cause for durability-related issues in construction. In order to fully benefit from using dried products, engineered wood products in particular, care must be taken to prevent them from wetting during the shipping, storage, and construction. Building codes in North America require that the wood be not more than 19% at the time of installation or enclosure. Wood in indoor conditioned environment typically ranges from 5% to 12% MC (CWC 2005). Regarding the MC during construction in Coastal British Columbia, it was reported that the average MC of “S-P-F” dimension lumber (studs and bottom plates, “S-Dry”) was about 20% during wood-frame construction in the winter climate, before the building was completely protected from rain (Wang *et al.* 2013). However, there was a wide range in the MC depending on exposure degrees, with the higher readings above 30%. The average MC of lumber dropped to about 15%, with a much narrower range than that observed in the winter, under the summer drier conditions in the same area (Wang and Ni 2014). Most engineered wood products have MC lower than 15% during construction if they are well protected from rain or ground moisture.

4.2 Effect of Water Vapour

4.2.1 Typical Service Environment

The relative humidity (RH) is a key parameter for an indoor environment and it varies depending on the use of the space (e.g., residential, swimming pool, ice arena), HVAC (heating, ventilation and air conditioning), building envelope design, exterior climate, and other factors. For residential construction, 30%-50% is a typical range in Canada; however, the RH in winter in the Prairies and Central Canada can be lower than 30% (e.g., 15-20% in Prince George, Wang 2015b) but can be higher than 50% in the coastal climates (Finch *et al.* 2007). Improved airtightness, one of the measures to improve home energy efficiency, can cause elevated indoor RH without a properly functioning ventilation system.

For wood exposed at a construction site or built to be exterior, the amount of water vapour available in the air ranges from very low levels in cold and dry weather to very high levels under warm and humid conditions. Both extremes may cause problems. For example, the former leads to very low EMC and typically increased check development (see Section 5.4). On the other hand, a damp environment, such as that in the winter in Coastal British Columbia, requires more consideration for on-site moisture management due to the increased wetting but reduced drying potential.

Eurocode subdivides indoor conditions into three service classes (CEN 2004; Winter *et al.* 2014). Service Class 1 is a typical conditioned indoor environment, characterised by the RH exceeding 65% only for a few weeks per year at a temperature of 20°C; correspondingly the MC of most wood will not exceed 12% (e.g., ranging from 5% to 12%). The medium environment, Service Class 2 is for exterior sheltered condition or indoor unusually high humidity, such as that in a green house. It is characterised by the RH of the surrounding air exceeding 85% only for a few weeks per year, with the average MC of most wood not exceeding 20% (e.g., in a range of 10-20%). The most severe service environment, Service Class 3, is for exterior applications, such as balconies, wood bridges, or indoor damp applications where there is a high risk of vapour condensation, with the typical MC of wood ranging from 12 to 24%. Generally speaking, well insulated and conditioned buildings, which can include swimming pools if the humidity is well controlled, tend to have lower RH and consequently lower wood MC. For buildings which are partially open, non-insulated, non-heated including ice arenas, the inside environment will heavily depend on the exterior weather, typically leading to higher seasonal vapour condensation potential. In any building, there could be localized areas with high RH or high RH fluctuations, such as those that are close to and highly influenced by the exterior conditions. Those buildings should have well-functioning mechanical systems (e.g., dehumidifiers) to reduce the humidity level to avoid vapour condensation. The most risky areas in the buildings deserve special attention in design to avoid durability issues.

4.2.2 Interactions between Wood and Water Vapour

The humidity and temperature conditions in an ambient environment, including fluctuations, are the primary factors determining the amount of bound water and the moisture gradients inside a wood member. They have a large influence on the physical and mechanical properties, such as swelling/shrinkage, creep, and checking development. The environmental conditions also have a large effect on the drying ability once wetting occurs. Wood exchanges moisture only with the surrounding air when it is not in contact with liquid water. Wood loses moisture, which could include free water when present, and bound water, when the ambient humidity is low. The RH drops as the temperature increases with other factors remaining the same in an environment. The drying of wood is fastest under warm, dry, and ventilated conditions. On the other hand, wood may gain moisture from the surrounding air, increasing the amount of bound water, when the ambient humidity is high. The interactions with water vapour are called sorption, including both desorption, i.e., the loss of bound water, and adsorption, i.e., the gain of bound water. **For pre-dried wood, the moisture in the air does not introduce liquid water and will not increase the MC above the fibre saturation point, unless the vapour condenses on the wood surfaces under extreme conditions and the wood is then exposed to liquid water long enough**.

Under constant humidity and temperature conditions, the wood will achieve an EMC when it no longer gains or loses moisture (i.e., when there is a balance between desorption and adsorption). Because adsorption and desorption are much slower than typical fluctuations in environmental RH, in practice wood never reaches an EMC. However, the MC will normally fluctuate over a small range within a certain environment, and this stable MC can be considered an EMC in practice. Figure 1 shows the average EMC, i.e., isothermal sorption curves of solid softwood (e.g., S-P-F, Douglas fir) with changes in RH at two levels of temperature (with data based on FPL 2010). The EMC of wood is primarily determined by the RH of the environment. Other factors including temperature (under a given RH), wood species, and drying history all have small effects. Regarding species, the chemical compositions including the cell wall components (i.e., cellulose, hemicellulose, and lignin) as well as extractives have effect. For example, some extractives in western red cedar, i.e., the polar extractives including plicatic acid, were found to contribute to the low EMC and good durability of the wood (Stirling and Morris 2006). On average wood will reach a MC around 11% when the RH is about 60% and will equilibrate around 8.5% when the RH is about 45%, at a temperature of about 20°C. Figure 1 also includes the EMC of OSB, plywood, and a type of low-density fibreboard (with data based on Kumaran 2002). Wood-based composite products usually have an EMC lower than that of the parent wood material due to the added chemicals (e.g., adhesive, wax) and the high temperature treatment during manufacture (Onysko *et al.* 2010). Related to this sorption behavior, Appendix II provides typical MC ranges under outdoor sheltered or indoor environmental conditions in different climates in Canada (from CWC 2005, Table 5.3). A German study monitoring 21 non-residential timber buildings including indoor swimming pools, ice arenas, gymnasiums, agricultural, and warehouses showed that the average MC of timbers (mostly glulam) ranged from 4.4% to 17.1% (Winter *et al.* 2014).

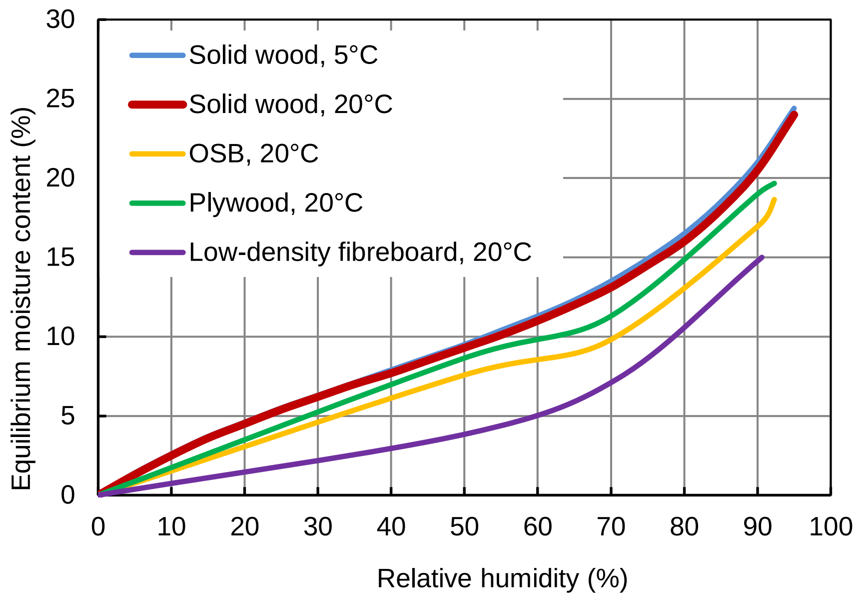

Figure 1 Representative isothermal sorption curves: equilibrium moisture content of solid wood and wood-based composites at various relative humidity levels (data sources: FPL 2010; Kumaran 2002)

There are always moisture gradients inside a wood member due to the fluctuating environmental conditions. The magnitude in the MC fluctuation largely depends on the wood species, product, size of the member, and distance from the surface under given environmental conditions. For example, when the humidity was changed cyclically between 65% and 90% with a duration of 7 days for each RH, (Sundström *et al.* 2011), for pine heartwood, the difference between the maximum and the minimum of MC was about 3% at a depth of 10 mm and was 1% at a depth of 45 mm. The heartwood of Scots pine had an average MC 1% lower than that of the sapwood or European spruce. The core of a large wood member is apparently well protected from fluctuations in the environmental conditions and remains stable in MC.

When the RH is high enough to be near-saturated (i.e., close to 100%), it becomes very challenging to control or measure the RH accurately. There have been controversies about wood EMC and the extent of capillary condensation under such conditions (Wang *et al.* 2012). Latest research using advanced technology shows that the amount of capillary water in wood is insignificant up to a RH of 99.5% (Engelund 2011), with the MC not significantly above 30%. Once wood is exposed to a more severe wetting source, such as rain and condensed water, the liquid water usually plays a more controlling role in the performance than sorption alone. Liquid water sources and their impacts are discussed in Section 4.3.

4.3 Effect of Liquid Water

Liquid water is the major source of damage for any buildings, not only wood buildings. Water damage claims, such as resulting from leaky or burst pipes, are one of the primary causes of rising propertyinsurance costs and are greatly concerned by the homeowners insurance industry[1]. For a wood building, there is additional concern about potential impact of wetting on the structural integrity and other issues.

4.3.1 Sources of Liquid Water

4.3.1.1 Rain

Rain is not only the major concern of wetting during construction, it also is the major cause of building envelope problems, such as those occurred in Coastal British Columbia from 1985 to 1995 (CMHC 1996). Factors, such as the total rainfall amount, season, rain durations, wind-driven rain intensity, and even rain drop size, are all important. For example, when most rain events occur in the winter, such as in the mild coastal climates, the moisture risk generally increases, not only due to the increased wetting potential, but also the reduced drying ability. By comparison, wood can dry quickly in the Prairies and Central areas after rain falls in the summer due to the overall warm and dry weather. However, biodeterioration can start quickly under warm conditions if wood gets wet.

4.3.1.2 Ground Water

Components in contact with the ground are typically subjected to severe wetting resulting from exposure to standing water and other moisture sources. Ground moisture should be managed during both construction (e.g., on-site storage) and in service (e.g., for components in contact with the ground or concrete).

4.3.1.3 Snow and Ice

Snow can be a significant wetting source in areas with heavy snow loads. It does not result in much wetting until it melts, so the most important measure during construction is to remove snow from wood before it melts. For the building envelope, issues may occur in areas where the thermal insulation level is low or where there is a large amount of air exfiltration, with excessive heat loss from the interior. The snow melt can run to cold locations where it freezes. This is how ice dams form at eaves in a cold climate. Blowing snow can also enter vents and holes in the building envelope that may be relatively well protected from rain.

4.3.1.4 Vapour Condensation

Vapour condensation occurs when air contacts a surface that is at a temperature below the dew point of the air. This is primarily a concern about the exterior elements of the building envelope, such as the exterior sheathing, resulting from exfiltration of indoor humid air in a heating climate. Condensation may also occur at the interior elements in a cooling climate, resulting from inward vapour drive for an air-conditioned building, particularly after rain events when water-absorbent cladding (e.g., brick, stucco) is used.

[1] Some water damage-related facts are mentioned on: http://leakdefensesystem.com/water-damage-stats/

4.3.1.5 Incidental Indoor Sources

Severe wetting can occur indoors due to events, such as activation of sprinklers or leak of a water pipe. Quick action afterwards including remedial efforts can minimize the wetting time and facilitate the drying. On the other hand, a higher moisture risk can be caused by small water leakage (e.g., from plumbing, bathroom tubs) that is not noticed or addressed until severe damage has occurred. A flooding event is the most catastrophic, particularly when it lasts for a long period (e.g., days, weeks).

4.3.2 Wetting and Drying Behaviour Associated with Liquid Water

Compared to sorption, absorption of liquid water can induce much faster changes in the MC of wood, including increasing the MC above the fibre saturation point. Wetting caused by liquid water is therefore typically a large concern for wood properties and performance, particularly regarding the durability performance. The wetting and drying potentials of a given material depend on weather conditions, such as the frequency of rain (e.g., rainy days during construction), rainfall amounts, humidity levels, wind speed, and temperature. Wood usually needs time to absorb water; the period of wetting is therefore often more important than the total amount of water falling on the surface to increase its MC (Scheffer 1971). Related to weather conditions and exposure degrees, the orientation and location of components have a large impact on the wetting and drying potentials. For example, horizontal components, such as roofs and subflooring, are often subjected to more rain (and pooling) and need more time to dry after wetting events. Mass timber roofs are particularly slow in drying if wetted wood members are covered with roofing materials, which typically have low vapour permeance. By comparison, vertical components, such as wall sheathing, typically receive smaller amounts of rain (mostly wind-driven rain) and can also dry relatively quickly with more permeable moisture barriers.

In terms of internal factors, different materials/assemblies can have highly varying water absorption rates and capacity, as well as drying, largely depending on inherent factors, such as wood species; manufacture; dimensions; presence of internal voids; exposure of end grains; adhesive and wax contents for composite materials; and surface treatment, if there is any. All these factors can affect the resistance to water absorption at the surfaces and the internal resistance to moisture movement and distribution. For example, composite materials, such as plywood, OSB, PSL, LSL, OSL, and LVL, have micro-voids and exposed end grains inside and consequently are more susceptible to deep wetting. Solid wood products, such as glulam and CLT, in general, have low wetting potential. However, they are also slow in drying once water is allowed to penetrate deeply, or wet wood is covered with materials with low vapour permeance (McClung *et al.* 2014; Wang 2014; Wang 2016). The presence of gaps in a product (e.g., composites, nail-laminated timbers, CLT, glulam) or an assembly, particularly when the more absorptive sapwood (than heartwood) is adjacent, may become special concern for trapping moisture (Wang 2016). For example, tight joints (e.g. in non-edge-glued CLT and sometimes in glulam) create capillary water traps, permitting moisture penetration but limiting air flow. Larger gaps between joints, such as 5 mm for Norway spruce, were reported to improve the drying after wetting events (Fredriksson *et al.* 2012; 2013; Fredriksson 2013). See detailed discussion on wetting and drying potentials of different materials and assemblies in Reference (Wang 2015c).

The variations among wood species are mostly caused by the sizes and structures of wood cells, whether the cell lumens are blocked (e.g., by extractives), and whether the bordered pits between cells of softwood species are aspirated (Siau 1984; Skaar 1988; Johansson and Kifetew 2010). Water absorption is the rapidest in the longitudinal direction since most wood cells are tube-like cells along the grain that encourage capillary uptake. For example, 90-95% of a typical softwood species consists of tracheids, with the length ranging from 2.5 to 7.0 mm and averaging about 3.5 mm, and being about 100 times the diameter. Adjacent tracheids are connected by small openings, i.e. bordered pits, as a path for fluid movement. The number, shape and closed or open status of these pathways govern the permeability of the wood to a large extent. For softwood the ratio between longitudinal and transverse (tangential or radial) permeability can be between 15 and 80,000 based on testing using small specimens (Siau 1984). But the high longitudinal permeability mostly increases the MC of a wood member within approximately 100 mm from an exposed end grain and does not have much effect on the wood inside (Sundström *et al.* 2011). In the same species, the sapwood is typically more permeable than the heartwood since most pits in the heartwood are already closed or blocked after the heartwood dies in the tree. In the same growth ring of sapwood for the Pinaceae family (which provides most commercial softwoods such as pines, spruces and firs), the latewood, although having smaller cells, typically has higher absorption than the earlywood since most pits in the earlywood become closed during the drying processes (Siau 1984). In general most Canadian softwood species, such as S-P-F and Douglas fir, are quite refractory to water penetration. Based on the experience with pressure preservative treatment, water does not penetrate more than a few millimeters even after 6 hrs under a pressure of 1035 kPa, unless the wood is mechanically perforated before treatment (Morris 1991). But prolonged exposure will certainly lead to deep water penetration. See Appendix III for the permeability of commonly seen softwood species in North America. Other factors could affect the permeability, for example, the blue-stained sapwood of beetle-killed lodgepole pine is more permeable due to the fungal attack (McFarling *et al.* 2006).

5 POTENTIAL CONSEQUENCES OF WETTING

Prolonged wetting could lead to durability issues, such as staining, mold growth, and ultimately decay, which affects the structural performance. This section summarizes the critical conditions for such consequences to occur and their impacts on the properties and performance. The most important conditions for fungi to grow in wood are suitable moisture and temperature conditions. Severe wetting alone can affect the mechanical properties of a composite material due to the damage to the adhesive bonding. Various models that have been developed for predicting service performance (e.g., mold growth, decay) and service life are not included in this report since very few are mature for design use. Termite damage, which may have connections with moisture, is beyond the scope of this work. Deterioration caused by fungi is overall a larger threat than insects for wood construction (FPL 2010, Chapter 13), particularly in Canada, where termite hazard is present only in some southern Ontario cities and some of the drier areas of British Columbia (e.g., the Sunshine Coast and the Okanagan).

5.1 Mold and Staining

Mold growth and fungal staining can occur on wood members when there are suitable conditions (Morris 1998; FPL 2010, Chapter 14). These fungi live on non-structural components of wood, such as starches in cell lumen, and therefore appear on sapwood more often. They primarily affect the appearance rather than the strength of wood. **These fungi generally require a high RH, such as higher than 90%, and warm conditions to grow fast**. Research shows that mold needs a minimum surface RH (sometimes called “water activity”) around 80% to grow on wood at a temperature of 20-25°C; under such marginal conditions, it could take months or longer to initiate on non-resistant wood materials, which could be detected probably only by microscopy (Viitanen and Paajanen 1988; Nielsen *et al.* 2004; Yang 2005). Compared with the heartwood of most species, the sapwood as well as wood-based composites, such as fibreboard and OSB, tends to be more susceptible to mold growth; fluctuating RH conditions, such as between 95% and 65%, generally retard the growth compared to the higher RH conditions (Yang 2005). For buildings, incidents of mold growth or other types of fungal staining occurring during construction or in service are more often associated with wetting caused by liquid water sources, such as rain penetration, ground source moisture, vapour condensation (e.g., resulting from air exfiltration), and pipe leakage. Aside from fungal staining, wood may also develop chemical staining. For example, iron stain is caused by presence of iron in combination with moisture (Figure 2). For appearance products and exposed mass timbers, staining often requires costly remediation efforts to remove the affected surface areas and to refinish. Attention should be paid to preventing wetting incidents and improving the drying ability, e.g., through improved ventilation.

Figure 2 Iron staining on glulam resulting from on-site wetting and contamination with iron particles

5.2 Structural Performance

The loss or gain of moisture below the fibre saturation point affects the mechanical properties of a wood member within a relatively small range. Decay, resulting from prolonged wetting, can cause significant strength reduction. This section summarizes the structurally related behaviour under ambient conditions and under severe wetting conditions, with or without decay. The conditions for decay to start and progress are reviewed.

5.2.1 Impacts of Changes in Ambient Environment

Timber structures are affected by the environmental conditions to which they are exposed. The environmental conditions, RH in particular, typically fluctuate, leading to changes in the wood MC. Most mechanical properties, such as bending, compression parallel/perpendicular to grain, and tension perpendicular to grain, increase with decrease in MC below the fibre saturation point (FPL 2010, Chapter 5). Most strength values available to designers are based on standardized short-term testing, typically at a wood MC of 12%. Very low and fluctuating MC may cause other issues, such as excessive shrinkage and checking (see Section 5.4). Checking, for example in glulam, typically has limited influence on the structural performance, particularly when the check is parallel to the grain (Yeh *et al.* 2006). However, when a check exceeds a certain limit, for example, if the depth of a check in the side face of a glulam beam is more than one third of the width of the beam, or the length of a check or split in the end face is more than one-half the depth of a member, consulting with a design professional is required to ensure the structural performance (APA 2006; APA 2007). Excessive checking should be particularly prevented from weakened portions of a timber member, such as notches, other holes, or mechanical connections.

Much attention has been paid in Europe in the past decade to the potential impacts that can be caused by checking. Based on surveys of wide-span structures in Germany following the collapse of Bad Reichenhall ice arena (Dietsch *et al.* 2006), a lack of consideration for environmental impacts in design, leading to high or low MC, was identified to be one of the major reasons for building failures. The potential impacts of excessively wet conditions are obvious, but the potential impacts caused by severe MC fluctuations and checking are often neglected by designers. The survey results led to revisions in the design standards in Europe. A concept "effective width" was introduced by multiplying the nominal width with a checking-related safety factor kcr. For glulam and solid timbers the recommended value of kcr is 0.67 in the Eurocode (CEN 2004). However, this design method for reducing the shear capacity of glulam was reported to be too conservative (Sundström *et al.* 2011). The shear performance of over 100 full-size glulam beams was assessed in Sweden in a process when the ambient humidity was reduced from 90% to 30%. It was found that the actual mean MC affected the shear strength but the moisture gradients and checking caused by the varying humidity had no effect on the shear strength. The coating on the glulam, when present, showed minor effects on the moisture gradients and had no effect on the shear strength.

Since tension failure perpendicular to grain is the most common failure mode for glulam resulting from moisture induced stresses, the effects of fluctuating humidity conditions on tensile strength perpendicular to grain have been extensively investigated in Europe. Wetting leads to larger stresses in wood than the subsequent drying. The stresses can also relax and decrease quickly, such as within a few days (weeks) (Jonsson and Thelandersson 2003; Jonsson 2004; Angst 2012; Angst and Malo 2012a; b). As further discussed in Section 5.4, the arising stresses and checking development depend highly on the growth ring configurations and location of pith (if present) in the lamellas. It was reported the use of self-tapping screws as a measure to increase the load bearing capacity of glulam beams was able to significantly reduce the tensile stresses arising in the cross section centre during wetting. Based on withdrawal testing for self-tapping screws on CLT panels (the screws were inserted in the plane side of three layered CLT) (Silva *et al.* 2014), the withdrawal resistance was constant when the MC ranged from 8% to 12%, but reduced when the MC increased to 18%.

Probably a more important design consideration is the time-dependent deformation, i.e., creep. Increased MC or large MC fluctuations accelerate creep, for example, for transverse compression of wood (Bodig 1966; Kunesh 1966). Regarding the influence of wood MC and environmental temperature, it was reported that the temperature would affect the elastic and time-dependent responses of wood equally; but changing moisture had a larger effect on the time-dependent response than on the elastic deformation (Engelund and Salmén 2012). The simultaneous action of load and changing MC is called mechano-sorptive effect. Long-term tests of small clear wood under tensile or compressive loads in cyclic ambient environments found that the mechano-sorptive strain can be 10 times higher than the elastic strain (Svensson and Toratti 2002). A study (Hoyle *et al.* 1994) to compare the creep under a constant RH of 65% and cyclic RH changing between 90% and 40% found that the relative creep of the glued laminated material tested increased from 40% to 72% as a result of the cycling humidity, and the increase for the solid sawn lumber was from 200% to 400% under the same conditions. It was believed by the authors that the gluelines in the glulam specimens partially contributed to the improved performance by retarding the response to the changing humidity and reducing the MC change rate inside the beams, in addition to the better distribution of wood defects by lamination. However, the permeability of gluelines was not assessed. For such long-term behaviour, the RH fluctuations, dimensions of wood members, type of loading, and age of wood may all have effect (Srpčič *et al.* 2015). For example, juvenile wood typically increases the deformation and checking development when it is loaded and exposed to fluctuating environmental conditions. CLT is more susceptible to creep under load than glulam. The duration of load and creep behaviour of CLT was extensively tested at FPInnovations to assist in building design (Pirvu and Karacabeyli 2011).

5.2.2 Impact of Severe Wetting

Wetting alone may affect the structural performance (as well as residual swelling, Section 5.4.2) of composite materials, when it is severe enough to causes damage to internal bonds provided by the adhesive. Decay resulting from prolonged wetting can greatly affect the structural performance (Section 5.2.4). Excessive wetting should be prevented during construction and in service to prevent any adverse effect. Action should be taken to dry, possibly with other remedial efforts, once wetting occurs.

Plywood and OSB are commonly used as structural sheathing materials for walls, floors, and roofs. They are both highly absorptive of liquid water compared to solid wood or thicker and denser panels (Wang 2014). In a field test in Corvallis, Oregon by horizontally exposing plywood and OSB during the wet season from January to June, it was found (Meza *et al.* 2013) that exposure to rainfall almost immediately led to gains in MC and thickness swelling, as well as reductions in the bending properties after reconditioning at 23°C and 65% RH. The maximum load carrying capacity of the plywood and the OSB specimens decreased by 17 and 4%, respectively, after 6 days of exposure, when there was only 3 days of rain with a total rainfall amount of 8.1 mm. The modulus of rupture (MOR) of the OSB dropped further by about 30% after 100 days of exposure; but that of the plywood remained steady after the initial reduction. A similar field exposure was conducted for I-joists made with LVL flanges and OSB webs (King *et al.* 2014). I-joists are typically designed for long-span loading under indoor conditions but they could be subjected to wetting during construction or in service (e.g., by activation of sprinklers). The bending properties as well as the ultimate tensile strength of the I-joists were assessed over time using a six-point bending test. It was found that the bending strength reduced due to the exposure to rainfall. The variations in the bending performance greatly increased after 27 days of exposure and the MOR showed significant reductions after 65 days, mostly resulting from swelling of the OSB webs. The exterior exposure did not appear to cause much effect on the tension properties of the I-joists.

Leichti *et al.* (2002) investigated the potential impacts of wetting, simulating flooding, in laboratory on the mechanical properties of OSB and the structural capacity of shear walls built with Douglas fir framing and OSB sheathing. The OSB specimens were soaked in water for a maximum of 7 days, air-dried and tested for embedment strength, edgewise shear strength, and shear modulus. It was found that the most degradation in the OSB properties occurred in the first 48 hr of water submersion. For example, the embedment strength reduced by almost 40% in the first 48 hr and then remained stable for the remaining 120 hr of soaking. On the other hand, the shear walls showed very different behaviour. Soaking of the sill plate and the lower 1 m of the walls for 7 days did not appear to reduce the shear wall capacity, the energy absorption, or change the yield mode. However, the stiffness of the walls was reduced resulting from the reduced embedment stiffness of the OSB sheathing.

5.2.3 Conditions for Decay to Occur

Decay resulting from the growth of wood-rotting basidiomycetes can cause significant strength reduction and is the largest wetting-related durability concern for wood structures. Wood can be infected by germination of fungal spores, which are available in the air, or direct infection by hyphae spread from adjacent infection sources, such as soil or pre-infected wood. The growth of decay fungi requires a suitable food source, adequate moisture, a warm condition, some oxygen, and limited competition from other microorganisms. Among these, the optimal growth temperatures for most decay fungi are in the range of 21 to 32°C, which are often found under building service conditions. The moisture supply is typically the most limiting factor for decay development for a given wood member. In terms of the minimum moisture condition, Zabel and Morrell (1992) stated that fungi were not able to grow effectively when the MC was below 28%-30%. Covington *et al.* (1992) suggested that a MC of 26% marks the risk level for decay initiation in sound wood; but decay might continue at a MC ranging from 22% to 25% if the wood is pre-infected. Carll and Highley (1999) provided a comprehensive review of conditions for decay to occur and develop in wood products used in construction above ground. They concluded that neither germination of basidiomycete spores nor growth of fungal hyphae could occur at moisture conditions much below the fibre saturation point. The conditions for decay initiation and progression were also summarized by Wang and Morris (2010).

Disparities often occur between testing studies and real service conditions in terms of decay. Many laboratory and even some field decay tests are more or less accelerated by purposely creating favourable conditions for fungal growth, such as a suitable MC, a warm environment, pre-sterilization to minimize fungal competition, increased fungal intensity by inoculation of specific mycelia or spores, susceptible wood (e.g., small sapwood blocks), and added nutrients. Based on laboratory testing of unsterilized sapwood of Norway spruce and Scots pine using inoculation by both mycelia and spores of a brown-rot fungus (*Coniophora puteana)* at a temperature of 20°C, it was found (Viitanen and Paajanen 1988) that the fungus grew only when the RH was above 96%, with a wood MC of about 25%. At this marginal RH the growth of fungus was very slow and the weight loss of wood was negligible after 1 year. However, for some technical reasons probably related to computer simulation, the curves of the critical response times generated based on the laboratory testing indicated somehow lower minimum RHs for decay initiation at various temperatures (Viitanen 1997; Viitanen *et al.* 2009). Page *et al.* (2003) conditioned Radiata pine sapwood to achieve a range of MCs by careful wetting, equilibration and sorting, and then inoculated the material with wood blocks infected with a brown-rot fungus (*Antrodia Xantha* or *Oligoporus placentus)*. No decay initiation was found at a MC of 24% or 25% during the test period of over 26 weeks; but 26-27% MC led to successful decay initiation in 4 weeks.

To generate critical MC conditions for decay initiation in Canadian wood products to support development of damage functions of hygrothermal models in cooperation with the building science community, FPInnovations tested aspen OSB, Canadian softwood plywood, and solid-sawn Hem-Fir or spruce, all unsterilized, under constant or fluctuating moisture conditions (Clark *et al.* 2006; Wang *et al.* 2010; Wang and Morris 2011). It was found that at a RH of 90% or 95%, the hemlock heartwood, OSB or plywood did not show any decay, or loss in stiffness or strength in a test period over 3 years, despite repeated inoculation with decay fungi. However, the OSB at near-100% RH conditions (with a MC of about 27%) started losing stiffness and strength in 36 weeks. At a MC of around 40%, the OSB and hemlock started to decay in less than 21 weeks; but the plywood did not decay during the test period of 74 weeks. The higher decay resistance of plywood in the test was probably partially attributable to its alkaline nature resulting from the phenol formaldehyde adhesive used. This may not be the true performance in field where severe wetting occurs and washes out the alkaline chemical. More recent work using a pile test (Meyer and Brischke 2015) suggested that decay could occur at a much lower MC, particularly by one white-rot fungus which typically requires a high wood MC. The mycelial inoculum was growing from a moisture source and could conceivably have transported moisture to the wood in the test. Furthermore the threshold for decay was taken as 2% weight loss but wood is known to have up to 3% by weight of non-structural carbohydrates that can be consumed by even non-decay fungi.

To summarize, **research studies have shown that the critical MC for decay to initiate is around 26%, which can be understood as the low end of the fibre saturation point, when all other conditions are favourable for fungal growth**. It takes approximately 6 to 12 months for wood products (heat pasteurized during manufacture) to get infected by decay fungi spores under marginal moisture conditions and it may take further 3 to 6 months for detectable strength loss to occur. These times may increase considerably if other conditions are not favourable for decay fungi, such as a low temperature or a low oxygen level (e.g., under water submerge), or simply the wood is decay-resistant (i.e., naturally durable or preservative treated). However, when there is a larger amount of free water available, for example with a MC ranging from 40% to 80%, decay can occur rapidly (e.g., in weeks) in susceptible wood species, causing reduction in the mechanical properties.

5.2.4 Impact of Decay

Among mechanical properties, impact-related strength, such as toughness and impact bending, is the most sensitive to decay. Decay has the least effect on shear and hardness, and an intermediate effect on other properties (Wilcox 1978; FPL 2010). For example, based on laboratory testing using small wood specimens and pure culture, the losses in toughness can range from 6% to over 50% by the time of a weight loss of only 1%; the toughness may drop to zero when the weight loss reaches 10%, when most other strength losses may exceed only 50% (Wilcox 1978). Note decay may be detectable only under a microscope when the weight loss is smaller than 10% (FPL 2010), although weight loss is often used as an indicator of decay in laboratory testing. As mentioned above most decay tests are based on small wood specimens or assemblies under aggressive inoculation of cultured mycelium, together with other favourable conditions. Testing results are not always consistent between different tests and may also not be applied to large members of a building. Moreover, decay in one component of an assembly or a structure may not have a large impact on the performance of the entire system.

Gonzalez and Morrell (2012) studied the impacts of environmental conditions including incubation temperature and wood MC ranges on the modulus of elasticity (MOE) and modulus of rupture (MOR) based on a third-point bending test. Three wood species including Douglas fir heartwood, western hemlock, and southern pine sapwood, in the form of small beams, were first sterilized by oven drying. Each beam was wetted under controlled conditions to target a MC range, 30-40, 60-80, or 100-130%. The material was then inoculated in a hole in the middle using cultured mycelium of one of the two brown-rot fungi, *Gloeophyllum trabeum* or *Postia placenta*, or a white-rot fungus, *Trametes versicolor*. The 2 mm hole, drilled 5 mm into a tangential face and 80 mm from the end, would be located in the neutral axis during the bending test (i.e., perpendicular to the loading direction). The beams were incubated at a temperature of 15°C, 25°C, or 35°C for different periods ranging from 6 to 36 weeks. The study found that the MOE was more sensitive to the fungal attack than the MOR. The white-rot fungus caused MOE losses that were comparable to those caused by the brown-rot fungi but had much smaller effects on the MOR. The three MC ranges showed little influence on the decay rates, being all above the fibre saturation point. Regarding the effects of temperature, the fungal damage appeared to be the slowest at the lowest temperature tested, i.e., 15°C, but did not show much differences between 25°C and 35°C. The natural durability of wood, i.e. the Douglas fir heartwood being the most durable among the three species tested, also influenced the fungal effect.

Wang *et al.* (2005) investigated the effect of decay on mechanical properties of Hem-Fir plywood. Small specimens were first oven-dried and then soaked in water under a pressure to achieve a MC range of 80-90%. They were inoculated with one of the three fungi, *Gloeophyllum trabeum*, *Postia placenta*, or *Trametes versicolor*, and incubated at 30°C for a duration between 5 and 15 weeks. The specimens were oven-dried again to assess the weight loss and tested for bending performance (MOR/MOE) after conditioning at 20°C and 60% RH. It was found that both MOR and MOE significantly decreased, with a larger reduction in MOR than in MOE, when there was a modest weight loss. Of these three fungi, *Postia placenta* caused the largest weight losses but the least reductions in MOR or MOE. At the longest exposure of 15 weeks, the reduction in MOR was 43% at a weight loss of over 4.1%. Exposure to *Gloeophyllum trabeum* led to the most severe loss in the bending performance. The reduction in

MOR was over 66% at a weight loss of 3.6%. Therefore these two brown-rot fungi showed very different effects. However, it was found that it could be difficult to differentiate the effects caused by fungi from those by wetting for such a composite material. The control plywood specimens of this study showed that wetting alone could lead to substantial reductions in the bending performance (covered in Section 5.2.2). The reduction in MOR was about 25% and that in MOE was about 19% after the specimens were stored for 15 weeks after the initial wetting.

Given the importance of shear walls to the lateral resistance of a structure under high wind or earthquake conditions, a few studies were carried out to simulate potential impacts of prolonged wetting and decay on the shear wall performance. Kent (2004; *et al.* 2004) assessed various levels of decay resulting from inoculation of a brown-rot fungus, *Postia placenta*, and its effects on the performance of small shear wall assemblies built with Douglas fir framing and aspen OSB. It was found that the lateral capacity was primarily controlled by performance of the OSB, since it decayed much faster than the framing. However, the lateral connection generally showed surprisingly robust performance through the early and intermediate stages of decay. But the performance started degrading at an increased rate when the weight loss of the OSB sheathing exceeded 12%, after incubation for 20 to 30 weeks. In a similar study, the impacts of wetting only, and of combined wetting and fungal attack caused by brown rot (with inoculation of *Gloeophyllum trabeum*) or white rot (with inoculation of *Trametes versicolor*) were assessed over a 35 week period in the laboratory (Melencion and Morrell 2009). The small shear wall assemblies were built with studs of Douglas fir or Engelmann spruce, and sheathing of aspen OSB, Douglas fir plywood, or southern pine plywood. The assemblies were first soaked in water for 30 days to generate different levels of MC for the different materials involved before autoclaving, inoculation, and subsequent incubation. It was found that the presence of mycelial growth was not an indicator of substantial wood degradation, and the white-rot fungus had no significant effect on the maximum load capacity in spite of intensive mycelial growth. The brown-rot fungus, however, caused significant reduction in the shear capacity. As discussed in Section 5.2.3, fungal colonization requires suitable conditions and does not always succeed even under favourable test conditions created in laboratory (King *et al.* 2015).

In real wood structures the impact of decay is more complicated and depends on different factors, such as the size of a wood member, loading conditions, fungi involved, location and intensity of the attack. Again appearance of decay does not reflect the true residual stiffness or strength. It was reported that depending on the location of decay in a wood beam, up to 14% of the cross section could be lost through decay, such as in the centre of the cross section, without causing significant reduction in the bending strength, and over 30% could be lost while retaining 80% of the residual bending strength or stiffness (Hedley and Bier 1994; Hedley *et al.* 2008). Assessing potential changes in the strength of a wood member that has been subjected to wetting or appears to have been attacked by fungi is very important in building retrofit. However, this can be very challenging due to the large variations involved, existing knowledge gaps, and a lack of assessment tools. See relevant information in Section 5.2.2, Impact of Severe Wetting, and Section 6.4, Condition Assessment and Remedial Treatment.

5.3 Variations between Wood Species and Products

5.3.1 Differences in Material Durability

Durable materials should be used for conditions with high moisture risk. Different types of wood have different inherent resistance against mold or decay, primarily due to the extractives in the wood. Sapwood is the newer part of a tree, closer to the bark. Generally the sapwood of any wood species has low natural durability. Heartwood is the inner, older part and no longer alive in the tree. The heartwood is more durable than the sapwood for a given wood species; however, wood species vary widely in the natural durability of their heartwood (FPL 2010). Of most commercial softwood species, the heartwood of S-P-F and Hem-Fir is less durable; the heartwood of Douglas fir and western larch is moderately durable; and the heartwood of species, such as western red cedar and yellow cedar, has relatively high natural resistance to decay. The heartwood of many tree species is darker in colour than sapwood, but the colour is not necessarily related to the natural durability of wood. For example, it was found that the decay resistance of western red cedar was not strongly associated with the colour of the heartwood but termite resistance was moderately correlated with the redness (Stirling *et al.* 2015). Most Canadian softwood species used for construction are predominantly heartwood, with relatively narrow sapwood. When the wood is not naturally durable enough to prevent fungal attack, it can be treated with chemicals, such as moldicides or preservatives, to improve its durability against mold or decay. Note many softwood species are refractory to penetration of preservatives even under high pressure conditions. More information about natural durability and preservative treatment can be found at www.durable-wood.com. See Appendix III for the permeability and Appendix IV for the natural durability of commonly seen softwoods in North America.

5.3.2 Differences in Moisture Properties and Structure of Products/Assemblies

As discussed in Section 4.3.2, inherent moisture-related properties of a product or an assembly, related to water absorption, entrapment, and drying potential, affect the durability of wood due to the critical importance of moisture to fungal growth. The locations which tend to come into contact with and trap liquid water, and dry out slowly, typically start to deteriorate sooner, especially under warm conditions. Related to practical applications, since end grains are much more absorptive than the transverse surfaces, exposing the ends of a vertical or even a horizontal member under exterior conditions, or embedding the end grain into or in direct contact with ground, moist concrete, or masonry, increases the moisture risk. End sealing can temporarily slow down water absorption. Exposing end grain and including small voids and gaps inside a product (such as composites, nail-laminated timbers, glulam, CLT) or an assembly may lead to localized water entrapment and decay. This was partially confirmed during the field testing of gamma joints made with various glulam products in Coastal British Columbia (Ingram and Morris 2015). It was found that after 8 years of exposure, most decay occurred inside the joints resulting from trapping moisture and reduced drying, and some decay started at the horizontal top end of the vertical member due to exposure of the end grain. Decay typically occurs where end grain is in direct contact with another wood component or other moist material. However, if the end grain is exposed to rain and drying winds, decay fungi may colonize at the end grain but decay typically advances more rapidly between 30 and 100 mm from the end where the wood stays wet the longest. Edge gluing between boards in CLT or glulam (i.e., between multiple pieces of side-by-side lumber in the same lamination) may help reducing such gaps; however, the potential of checking may arise due to the further restriction provided by adhesive. Checking may also trap moisture in timbers used in exterior exposure, particularly when a timber is exposed horizontally. Protecting timbers from direct exposure to the weather, rain in particular, is always the most important in order to achieve long-term durability.

5.4 Dimensional Issues

Wood shrinks with loss of moisture and swells upon gaining moisture below the fibre saturation point. The dimensional changes vary among different products, wood species, within the same species, and even within the same tree. Differential shrinkage, residual swelling of composites resulting from wetting, and excessive checking development during cyclic wetting and drying conditions may need to be taken into consideration in building design or during construction. Some wood products, particularly those with relatively high initial MC, may develop warping and other defects during the subsequent drying process.

5.4.1 Design for Differential Shrinkage

For predicting differential shrinkage in design, detailed information is provided in Chapter 5 of the Mid-rise Wood-Frame Construction Handbook (Ni and Popovski 2015). Wood is an anisotropic material in terms of shrinkage and swelling. It shrinks or swells considerably more across the grain than in the longitudinal direction, with the amount almost in direct proportion to the moisture change. For example, the average shrinkage in the tangential direction (in the direction of the annual growth rings) of spruce from a MC of 19% to 8% is about 2.7% (of the dimension) and the average shrinkage in the radial direction (in the direction across the growth rings) is about 1.3%. Over the same MC range, the average shrinkage of Douglas fir in the tangential direction is about 2.9% and that in the radial direction is about 1.9% (Figure 3, data based on Jessome (1977)). It is recommended to use an average shrinkage coefficient of 0.25% per 1% change in MC for cross sections of softwood dimensional lumber or sawn timbers (Ni and Popovski 2015). The shrinkage amount in the longitudinal direction is typically very small and can be neglected in design in most cases. Differential shrinkage also occurs between sawn wood and engineered wood products. Minimal shrinkage can be expected for an engineered wood product if the MC during manufacturing is very close to the EMC in the service environment. It was found from field monitoring that glulam columns were extremely dimensionally stable in the longitudinal direction, without any horizontal wood members in the load path; CLT walls were also very stable along the height (Munoz *et al.* 2012; Wang 2015b). A small amount of swelling may occur if the MC of wood increases resulting from incidental wetting or high humidity construction conditions (Wang and Ni 2014). However, there is very limited data available about MC adaptation or shrinkage coefficients of most engineered wood composites, such as PSL, LSL, LVL, OSL, and in-plane CLT. These products merit testing given the fact that more and more engineered wood products are used, in mid-rise and taller buildings in particular.

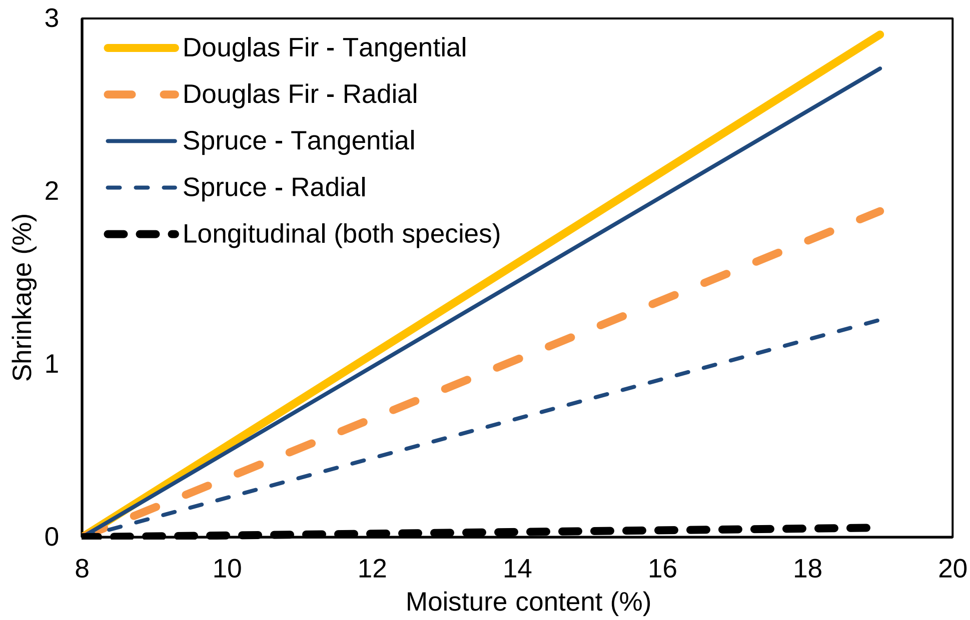

Figure 3 Shrinkage of two wood species in major grain orientations

5.4.2 Residual Swelling

For a composite material, severe wetting involving liquid water and subsequent drying may damage the internal bonds provided by the adhesive and consequently cause residual swelling after drying. For example, OSB subfloor swells substantially if the panels are exposed to liquid water sources during construction or in service and significant residual swelling will remain after drying. This may require sanding the entire floor to achieve a flat and uniform surface prior to installation of floor finishing. When OSB is exposed to cyclic humidity conditions, the largest swelling hysteresis or residual thickness swelling occurs during the first adsorption cycle (Wu and Lee 2002). The swelling rate generally increases with increase in the MC level or panel density. Although it cannot be completely prevented, the swelling of OSB can be reduced by manufacturing measures, such as using a more effective resin (e.g., isocyanate types of adhesive instead of phenolic formaldehyde (PF)) or increasing the resin content (Taylor *et al.* 2008). It was reported that the thickness swelling of aspen OSB exceeded 15%, and those of pine-based OSB and particleboard were about 10%, all based on a same level of PF, when exposed to the outdoor conditions in Japan for 2 years (Kojima *et al.* 2009; Kojima and Suzuki 2010). By comparison, the thickness swelling of PF-based plywood and methylene diphenyl diisocyanate-based medium-density fibreboard remained below 3% over the same period of time. For panel products edge sealing is a practical solution to temporarily slowing down vapour sorption and water absorption and may consequently reduce the extent of swelling.

5.4.3 Checking Development

For mass timber products, such as sawn timbers, glulam and CLT, there may be concerns from the occupants/owners of the building when large checks or splits occur. Fluctuations in the environmental conditions (e.g., RH) result in inhomogeneous moisture distribution and stress inside a wood member.

For example, a reduction in the RH in service first dries the outer parts of a timber. The consequent shrinkage imposes compression to the inner wood. On the other hand, when the humidity increases, or the wood is exposed to liquid water, the surface tends to expand first, generating tensile stresses for the core. The stresses, particularly those occurring during wetting, could exceed the strength of the wood and lead to checking. The initial MC of wood and the environmental fluctuations both matter in this regard and most checking occurs in the first or first few years in service. An effective measure to reducing such issues is to avoid extremes in the environment (e.g., through humidity control) and to allow the wood to adjust to the service conditions slowly, particularly in the first year. As discussed in Section 5.2.1, checking rarely affects the structural integrity in service and it is also typically taken into consideration in design. When checks affect the appearance of an exposed member, an elastomeric filler may be used with the tone to match the finishing colour (APA 2006).

Glulam is the most commonly used engineered wood products in non-residential structures. Similar to other engineered wood products, it is typically much more dimensional stable and less likely to check compared with sawn timbers. Much attention is already provided during the manufacturing to prevent checking. For example, each lamella is dried to a low MC, typically ranging from 11% to 15% to match the EMC in service, and individually checked for quality control before gluing. However, changing moisture gradients, particularly for a large cross section member, may lead to progressive check development, especially when free shrinkage is hindered by the gluelines or fasteners. Most checking or splitting occurs around the first few gluelines adjacent to an outer lamination or at the ends (APA 2006). Factors, such as wood density, the orientation and widths of growth rings, and location of pith, if present, could all affect potential checking development. For example, for lamellas cut from small logs near the pith, the outmost lamellas should be aligned that the pith side is faced out from the beam to reduce checking (Sundström *et al.* 2011). In a laboratory test involving accelerated checking under cyclic wetting (i.e., liquid water wetting) and drying (i.e. using heating lamps) conditions, it was observed (Pousette and Ekevad 2015) that the largest check tended to occur in the tangential surface of the lamella with pith in the middle, although the checking did not lead to shear failure in the subsequent bending test. The type of adhesive used also has impact on checking development due to the effect of bonding strength (Hassani *et al.* 2015). Checking development under outdoor conditions is also affected by the orientation of exposure based on an un-loaded test in northern Sweden (Pousette and Ekevad 2015). It was found that the lengths and widths of checks were generally larger in the southern exposure than those in the northern exposure except for white-painted beams.

6 SUGGESTED SOLUTIONS

With good understanding of the potential impacts of moisture on properties and performance of wood, appropriate measures should be taken to better manage the moisture risk during construction and in service.

6.1 On-site Moisture Management and Construction Sequencing

Extensive discussions on wetting and drying potentials and detailed guidelines for on-site moisture management have been assembled to help designers and builders assess the potential risk during construction and to identify appropriate actions to mitigate the risk (Wang 2015c). To summarize, the following basic storage or protection measures should be taken during construction of a mass timber building to reduce the wetting potential:

- Using off-site prefabrication to improve construction efficiency, minimize material waste at the site, and to reduce on-site exposure time
- Coordinating material delivery for just-in-time installation
- Keeping materials away from ground using dunnage and storing them in well-ventilated shelters
- Keeping wraps or using tarps to prevent rain ingress during construction; however, taking measures to accelerate drying once moisture gets inside

Advanced methods typically require more work and coordination and are more expensive. They should be taken into consideration for large composite or built-up members, which are highly susceptible to wetting and very slow in drying, and will require costly remedial treatments once wetting occurs. Examples of these measures include:

- Pre-installing protective membrane on members or assemblies
- Using a temporary roof to protect partial or the entire construction (see examples in Figures 4 and 5)

Figure 4 Using a tent to protect roof construction in a recent Vancouver project

Figure 5 Using a movable tent to protect the entire construction in Sweden

The shell of a building often provides the most effective and economical shelter for the wood inside and should be taken full advantage of during construction. This typically requires good sequencing and other considerations during construction. For example, an upper floor or a roof usually provides good protection to the floors and assemblies below, particularly when the joints and gaps are sealed (e.g., by using tongue and groove joints, or tape) right after the installation. Any standing water (or snow) should be removed from floors after large precipitation events. When the wood is dry enough, install roof sheathing and waterproofing membrane and exterior wall weather resistive barrier as quickly as the construction permits. The membranes should be sealed and made continuous at interfaces to prevent water penetration. Large openings in the roof and exterior walls, such as windows and doors, should be temporarily covered with translucent membranes (for providing natural light) to prevent blown-in rain (or snow) before final installation. Sufficient time should be provided for the wood members to dry and settle. Wet construction, such as concrete elevator shafts and concrete topping on subflooring (or on a roof), should be scheduled for completion at early stages to minimize adverse impact on the wood. When a roof built with mass timbers is exposed to rain, measures should be taken to dry them before installing any insulation or water proofing membrane above. It is difficult and slow for moisture to move through a mass timber component and to dry towards the interior once roofing is installed above. Walls, roofs, and any other parts must not be enclosed and finished until the framing materials have dried to an acceptable level of moisture, i.e., typically below 19% for wood. Insulation materials and membranes, spray foam and self-adhesive membranes in particular, should not be applied on wet wood. Mechanical methods, such as space heating, dehumidification, and forced ventilation, can be used to accelerate drying before and after enclosure. However, heating by using fuels, such as natural gas or propane, will add to the wetting load due to the extra moisture generated during burning of the fuel and may also become a construction fire concern. Use of advanced software, such as Building Information Modelling, may help optimize construction sequencing and improve construction efficiency.

6.2 Design for Durability

Decay can be prevented from initiation or progressing if wood is kept dry. The design aspects to achieving long-term durability can be generally summarized into 4 Ds: rain ***d***eflection, ***d***rainage, ***d***rying, and the use of ***d***urable materials (Hazleden and Morris 1999). These measures have become particularly important for modern timber construction to reduce the wetting potential and to improve the drying ability. Extensive guidelines regarding achieving durable and energy efficient building envelopes, including mass timber construction (e.g., CLT), are provided in the following publications:

- Guide for Designing Energy-Efficient Building Enclosures for Wood-Frame Multi-unit Residential Buildings in Marine to Cold Climate Zones in North America (Finch *et al.* 2013, free download)
- Building Enclosure Design Guide, Homeowner Protection Office, Branch of BC Housing (HPO 2015).
- CLT Handbook (Gagnon and Pirvu 2011; Karacabeyli and Douglas 2013. Chapter 10: Building Enclosure, free download)
- Technical Guide for the Design and Construction of Tall Wood Buildings in Canada (Karacabeyli and Lum 2014. Chapter 6: Building Enclosure Design, summarized in Wang and Finch (2014))

Comprehensive guidelines on achieving durable exterior wood are summarized in a document recently posted on the durability website: www.durable-wood.com (Morris 2015b). The risk for decay inside buildings is considerably more localized. Consequently, localized on-site non-pressure treatments may be appropriate for specific vulnerable locations, such as the base of columns on concrete slabs, particularly when enclosed. More information about non-pressure treatments is available on www.durable-wood.com.

6.3 Design for Leak Detection, Repair, and Replacement

General information on building maintenance has been developed and published by Canada Mortgage and Housing Corporation (CMHC, www.cmhc.ca) and the Homeowner Protection Office, Branch of BC Housing (HPO, www.hpo.bc.ca). Some specific considerations about maintenance and repair of tall wood buildings are provided in Karacabeyli and Lum (2014, Chapter 9). For mass timber construction, how to quickly and conveniently detect entrapped moisture during construction or water leaks in service has become a critically important issue, due to the larger capacity of timbers to hold and conceal moisture but the reduced ability to dry, compared with light wood frame construction. For example, small leakage from a water pipe or a roof may not be noticeable until extensive damage has occurred. Some measures may be taken in design to make it easier to detect water leaks and to accelerate drying once wetting occurs. For instance, vertical water pipes should not be embedded in a mass timber, such as CLT. For horizontal water pipes going through mass timbers (e.g., CLT), a protective plastic tube, surrounding the water pipe and sloped towards the direction from which any drained water can be easily noticed, may be used. For a roof, an interior ventilation gap may be introduced between the roof sheathing above and the mass timbers below for improved drying performance as well as easier leak detection, as built into the Wood Innovation and Design Centre in Prince George (Wang 2015b. Figure 6). Special non-destructive tools may be further developed to detect water leaks or entrapped moisture. A structure should also be designed for easy repair and replacement in case localized damage occurs. For example, for a balcony or a roof deck, a cantilevered structure by directly extending the interior floor joists and sheathing, or CLT floor panels, typically makes it difficult to repair or replace once decay occurs in the outside portion resulting from rain penetration. In addition, it causes extra thermal bridging and makes it challenging to maintain continuity in the weather barrier and the air barrier of the exterior wall. The design for a balcony or a roof deck can be improved through separating the exterior structure from the interior members. For example, a balcony can be supported by ledgers on the wall side and by posts at the exterior end, or built with independent structure and tied back to the wall framing only at intervals. The exterior elements may use preservative-treated wood for increased resiliency against decay.

Figure 6 Interior air space built in the mass timber roof of the Wood Design and Innovation Centre in Prince George accelerating drying and enabling leak detection

6.4 Condition Assessment and Remedial Treatment

For a structure, good design and workmanship are always the most important to reduce moisture risk and to prevent serious damage that can be caused by water penetration. Condition assessment, remedial treatment, repair, and replacement may be necessary and are important over the life span of a structure. Questions, such as “Has decay started” and “How strong are the original timbers”, often arise during condition assessment of in-service wood. Assessing structural conditions and identifying decay require specific knowledge and skills. Changes in visual appearance, such as colour or even growth of mycelium, may not necessarily tell the true condition of a wood member. The U.S. Forest Products Laboratory has developed an extensive manual on this matter, first published in 2004 and updated in 2014 (FPL 2014; a short summary provided by Ross *et al.* (2006)). FPL also offers a short course on in-service assessment in collaboration with a few universities in the United States. Credible information may also be found in other sources (Morris 1998; TRADA 2014). Basic procedures of field inspection include visual assessment and measuring MC of wood. Simple methods, such as hammer sounding and the pick test, may be used to determine whether the wood is still sound (see more details about the pick test at: www.durable-wood.com, Assessing Decay). More advanced methods, such as resistance drilling, stress wave, and ultra-sound techniques may be used by a professional to detect or locate decay inside a wood member (FPL 2014).

When decay is confirmed, its impact on the structural integrity may need to be further assessed. This is always challenging and few non-destructive tools are available for estimating the residual strength of decayed wood. Practitioners often face the difficult choice of only removing the decayed portion or replacing the entire member. The former reduces the cost but increases the potential liability; the latter may unnecessarily increase the cost and make it unaffordable for the owners. If it is confirmed that the damage is very small and does not affect the overall structural performance, localized repair may be used to restore the required strength. The bottom-line measure is to remove all infected wood, not only the obviously decayed, but also 60 cm beyond the end of any visible decay along the length of the member (Morris 1998). When the member provides a critically important role for the structural integrity, a safe measure is to remove the entire piece that contains even a small amount of decay. Identifying initial decay is not easy and incipient decay can cause severe damage, especially to the impact resistance (Section 5.2.4). Therefore for critical locations, removal of wood that appears to have been wet for a long time may even become advisable if dynamic properties are important. For mass timber construction, any repair and replacement may present many difficulties. For example, when decay is found in a CLT wall, floor, or roof, replacing any panel would be a large project and very costly. It is therefore very important to design such structures not only for long-term durability, but also for easy repair and replacement.

Since moisture is the fundamental source of decay, actions should always be taken to identify the source of wetting, fix the leaks, and to dry the wood as quickly as possible. For members that are concealed, for example, in an assembly, the other components, such as drywall and insulation, usually need to be removed to accelerate drying. Remedial treatment using a preservative, typically a boron-based product (e.g., soluble rods or spray application), may be used for wood to prevent decay, in case it does not dry out quickly or water penetration reoccurs in future. Detailed information about non-pressure preservative treatment is provided on the durability website: www.durable-wood.com.

Remedial efforts may also involve mold cleaning during building maintenance or retrofit. Related guidelines are available from Canada Mortgage and Housing Corporation (CMHC 2015), the Canadian Construction Association (CCA 2004), and other sources (e.g., New York City 2008).

7 CONCLUSIONS

The key points covered in this literature review include:

- Sorption is the interaction of wood with the water vapour in the ambient environment for pre-dried wood. The consequent changes in the amount of bound moisture (or “hygroscopic moisture”) affect the physical and mechanical properties. Sorption alone does not increase the MC above the fibre saturation point and does not lead to decay. The core of a large timber is well protected from the changes in the service environment.

- The fibre saturation point, averaging around 30% among wood species, marks the turning point of a relationship curve between the physical (e.g., shrinkage, swelling) or mechanical (e.g., strength, stiffness) properties and MC. Most properties change only below the fibre saturation point.
- A warm and humid environment, such as with the RH above 90%, facilitates growth of mold and staining fungi. Other types of staining, such as iron staining resulting from a combination of iron and moisture, may also occur on timbers.
- Absorption can introduce free water (or "capillary water") and increase the MC above the fiber saturation point. Incidental wetting is typically also the cause for mold growth, staining, and excessive dimensional issues. Severe wetting alone may affect the structural properties of wood-based composites, for OSB in particular, if the wetting damages bonding provided by the adhesive inside.
- Decay can cause significant strength reduction, for toughness and impact bending in particular. The marginal MC for decay initiation is around 26%, which can be understood as the low end of the fibre saturation point, when all other conditions are favourable for fungal growth. For a wood member in service, the effect of decay on the structural performance depends on different factors, such as the size of the member, loading condition, fungi involved, location and intensity of the attack.
- There are large variations among wood species, products and assemblies in trapping moisture and maintaining durability. Exposed end grain, interconnected voids, and tight joints may increase the likelihoods of moisture entrapment, slower drying, and consequently decay.
- Measures should also be taken in design, during construction, or building operation to reduce the moisture risk and increase the drying ability. It is also important to facilitate detection of water leaks in a mass timber building and to make it easier to repair and replace members in case damage occurs.
- Preservative-treated or naturally durable wood should be used for applications that are subjected to high moisture risk. Localized on-site non-pressure treatments may be appropriate for specific vulnerable locations.
- In addition to the durability issues, changing environmental conditions induce moisture gradients and stresses in wood. This may lead to severe checking in timbers, although it does not compromise the structural integrity in most cases. Measures should be taken during building operation to allow the wood to adjust to the service conditions slowly (e.g., through humidity control), particularly in the first year of service.

8 RECOMMENDATIONS

This review exercise identified that there is very little information about the potential impacts various wetting scenarios from construction to service could realistically have on mass timber products and systems. The following areas may deserve special attention in future research to fill in the knowledge gaps:

- To further develop non-destructive tools for detecting water leaks or entrapped moisture quickly and conveniently.
- To further assess wetting and drying performance, particularly for the new generation of engineered wood products including CLT and structural composite lumber.
- To generate applied information about the impacts of wetting and biological attack on the structural capacity of mass timber products and help improve both design and product development.
- To assess the behaviour of mass timber products under extreme environmental conditions, such as the typical dry service environment in northern climates, to improve building design.

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Appendix I.
Typical MC Ranges of Wood Materials at Manufacture

Group	Major material/assembly examples	MC range
A1	Dimension lumber, "S-Dry" (including "KD")	15-19%
A2	Solid-sawn timbers	Subject to supply agreement, typically above 30% for green timber posts
B1/B2	Glued-laminated timbers, such as glued-laminated timber (glulam) and cross-laminated timber (CLT)	11-15%
C1	Sheathing panels, such as plywood, OSB, fibreboard	6-12%
C2	Structural composite products, such as parallel strand lumber (PSL), laminated strand lumber (LSL), oriented strand lumber (OSL), laminated veneer lumber (LVL)	6-12%
D1	Prefabricated light wood framing using dimension lumber and sheathing panels	6-19%
D2	Nail-laminated assemblies built with "S-Dry" dimension lumber and sheathing panels	6-19%
D3	Prefabricated closed assemblies	6-19%

Appendix II.
Typical Equilibrium Moisture Content Ranges of Wood Materials in Different Climates of Canada (from CWC 2005)

Location		Average EMC (%)	Winter EMC (%)	Summer EMC (%)
West coast	indoors	10 – 11	8	12
	sheltered outdoors	15 – 16	18	13
Prairies	indoors	6 – 7	5	8
	sheltered outdoors	11 – 12	12	10
Central Canada	indoors	7 – 8	5	10
	sheltered outdoors	13 – 14	17	10
East coast	indoors	8 – 9	7	10
	sheltered outdoors	14 – 15	19	12

Appendix III.
Permeability of Major North American Softwoods

The particular structure of the cells for a given piece of wood will determine how permeable the wood is to chemicals. This table describes the permeability of common softwoods used in North America. The permeability ratings are:

1 – Permeable
2 – Moderately Impermeable
3 – Impermeable
4 – Extremely Impermeable

Tree	Permeability	Permeability	Predominant in the Tree
	Sapwood	Heartwood	
Douglas fir	2	4	Heartwood
Western Hemlock	2	3	Heartwood
Eastern Hemlock	2	4	Heartwood
White Spruce	2	3-4	Heartwood
Engelmann Spruce	2	3-4	Heartwood
Black Spruce	2	4	Heartwood
Red Spruce	2	4	Heartwood
Sitka Spruce	2	3	Heartwood
Lodgepole Pine	1	3-4	Heartwood
Jack Pine	1	3	Heartwood
Red Pine	1	3	Sapwood
Southern Pine	1	3	Sapwood
Ponderosa Pine	1	3	Sapwood
Amabilis Fir (Pacific silver fir)	2	2-3	Heartwood
Alpine Fir	2	3	Heartwood
Balsam Fir	2	4	Heartwood
Western Red Cedar	2	3-4	Heartwood
Eastern White Cedar	2	3-4	Heartwood
Yellow Cypress	1	3	Heartwood
Western S-P-F	2	3-4	Heartwood
Eastern S-P-F	2	4	Heartwood
Hem-Fir	2	3	Heartwood
Western Larch	2	4	Heartwood
Tamarack	2	4	Heartwood

Appendix IV.
Natural Durability of North American Softwoods

Species	Predominant in the Tree	Heartwood Durability
Western Red Cedar	Heartwood	Durable
Eastern White Cedar	Heartwood	Durable
Yellow Cedar	Heartwood	Durable
Redwood	Heartwood	Durable
Douglas fir	Heartwood	Moderately Durable
Southern Pine	Sapwood	Moderately Durable
Western Larch	Heartwood	Moderately Durable
Tamarack (E. Larch)	Heartwood	Moderately Durable
Western Hemlock	Heartwood	Slightly Durable
Eastern hemlock	Heartwood	Slightly Durable
White Spruce	Heartwood	Slightly Durable
Engelmann Spruce	Heartwood	Slightly Durable
Black Spruce	Heartwood	Slightly Durable
Red Spruce	Heartwood	Slightly Durable
Sitka Spruce	Heartwood	Slightly Durable
Lodgepole Pine	Heartwood	Slightly Durable
Jack Pine	Heartwood	Slightly Durable
Red Pine	Sapwood	Slightly Durable
Ponderosa Pine	Sapwood	Slightly Durable
Western White Pine	Heartwood	Slightly Durable
Eastern White Pine	Heartwood	Slightly Durable
Amabilis Fir	Heartwood	Slightly Durable
Alpine Fir	Heartwood	Slightly Durable
Balsam Fir	Heartwood	Slightly Durable
Western S-P-F	Heartwood	Slightly Durable
Eastern S-P-F	Heartwood	Slightly Durable
Hem-Fir	Heartwood	Slightly Durable

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