Guide for On-site Moisture Management of Wood Construction

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SUMMARY

This is a principles-based document that provides guidelines and relevant information about on-site moisture management practices that can be adapted to suit a range of wood construction projects. The document aims to help designers and construction companies/builders assess the potential for moisture-related issues arising during the construction phase of a wood building project and identify the appropriate actions to mitigate such risk. Wetting is the primary concern in most climates but an extremely dry environment can cause issues related to dimensional instability. Several categories of wood materials/built-up assemblies are classified in this document based on their properties related to water absorption, entrapment, and drying potentials. Different levels of protection strategies and methods are provided for consideration depending on the risk associated with durability, or discolouration of appearance components, resulting from wetting incidents. This guide focuses on mass timber construction but also covers light wood-frame buildings.

On-site moisture protection ranges from basic to advanced measures. Basic methods include using prefabrication as much as possible to reduce on-site exposure time, coordination of material delivery to reduce on-site exposure time, storing materials away from moisture sources, and providing simple protection, such as transit coatings, end-sealing, and covering with wraps and tarps. More advanced measures may include purposely utilizing the building itself, such as floors, roofs, and walls for sheltering, covering wood surfaces with pre-installed membrane, and installing a temporary roof to protect the construction. For a very dry climate, humidification may become necessary to reduce excessive dimensional changes.

The most critical factors that should be taken into consideration in determining appropriate on-site protection include:

- Construction weather conditions (e.g., rain, snow, relative humidity, temperature, wind)
- Wetting potential (water absorption, entrapment) of the wood materials/built-up assemblies
- Drying ability of the wood material/built-up assemblies
- Durability-related risks (e.g., mould, decay) after wetting and insufficiently rapid drying
- Appearance deterioration risks (e.g., discolouration, checking) of exposed wood members and finishing materials
- Location of the assembly in the building (e.g., interior/exterior wall, upper/lower floor, roof) and associated impacts on exposure and drying
- Cost of construction delay (or time to the building lockup stage)
- Cost of potential remediation resulting from incidental wetting
- Cost of forced drying (e.g., space heating, dehumidification) or humidification
- Cost of protection methods and required coordination

Overall moisture management during construction has become more and more important with the increase in building height and area, which potentially prolongs the exposure to inclement weather, and the overall increase in speed of construction which may not allow adequate time for drying to occur. In addition, the drying capacities of modern assemblies may have reduced resulting from increased insulation levels, or the use of membrane or insulation products with low vapour permeance.

In addition to selecting suitable materials/built-up assemblies and on-site protection methods, all assemblies should be designed to dry, in case wetting occurs during construction or in service. Ideally, multiple measures should be employed, as single measures are typically not fully effective all the time. Although design is an important step, the design aspect is not a focus of this document.

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1 INTRODUCTION

It is important to protect wood from water during the transport, storage, construction, and in-service stages to prevent potential issues, such as staining, mould, excessive dimensional changes (causing nail popping, drywall cracking), and even fastener corrosion and decay with prolonged wetting. Among these stages, the construction stage is likely the most challenging given the range of possible moisture exposure conditions and the inevitable site and cost constraints of a construction project. Limited guidance is available (BRANZ 2004; CWC 2004), particularly related to the construction of large and tall wood buildings in a rainy coastal climate, or wintertime in a northern climate with heavy snow loads. Moisture safety, especially during construction, deserves attention based on the experience with tall timber buildings in Europe (FII and BSLC 2014; Winter 2014). This document focuses on on-site protection against wetting by providing several categories of products/assemblies classified based on wetting and drying potentials, and different levels of on-site protection. Figure 1 illustrates a general process and considerations for assessing the wetting-associated risk and the subsequent decision making for moisture protection. However, it is also recognized that a very dry environment can cause issues, such as excessive checking and warping and may need measures to increase the humidity during construction or in service (see Section 5.3).

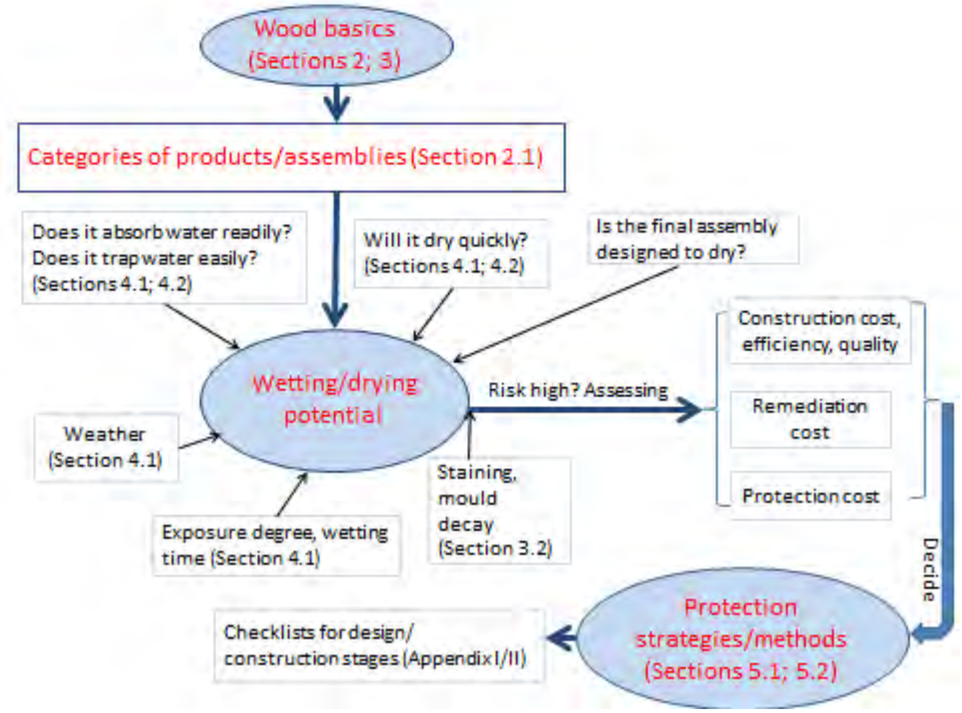

Figure 1 General sequence of assessing wetting and durability risks and determining on-site protection strategies and methods

Wood is in general quite resilient to moisture and moisture content (MC) changes if kept within certain limits. Wetting of wood framing during construction should not lead to problems if certain conditions are met. It is well known that a building assembly (e.g., roof, floor, and wall) should not be closed in until the wood has dried to an acceptable level of MC, typically below 19%[1]. The figure “19%” means that the mass of water present in a piece of wood is 19% of the mass of the wood after it has been oven-dried. In previous decades the use of green wood (i.e., the wood that is recently cut and has not been purposely dried), including dimension lumber and solid timbers, was the norm in most regions of North America (see the Canadian survey report, Garrahan *et al.* 1991)[2]. Exposing wood during construction, which added probably only a small amount of moisture to the wood, never got much attention. Most potential issues were solved, in a natural way, by the generally slower pace of construction at the time, which allowed wood in an assembly to dry before the assembly or building became enclosed. In addition, the traditional building envelope, which used to have very low levels of thermal insulation but typically high air movement and vapour permeance, also allowed the wood to continue drying after enclosure. Stick-built light wood-frame construction, mostly used for single-family houses and low-rise buildings, can generally accommodate wetting well, even for the dried wood commodities (e.g., dimension lumber and sheathing panels) seen on construction sites today. Most wood, particularly solid wood products with surface wetting only, and thin panels, can dry quickly under favourable environmental conditions. On-site wetting is therefore not a large concern for the traditional light wood frame construction.

However, moisture management during construction has become more and more important with the increase in building height and area, which potentially prolongs the exposure to inclement weather, and the overall increase in speed of construction which may not allow adequate time for drying to occur. In addition, the drying capacities of modern assemblies may have reduced resulting from increased insulation levels, or the use of membrane or insulation products with low vapour permeance. Even before enclosure, the drying of wood can be very slow in a cold and wet climate, especially for large wood members and built-up assemblies. Some construction companies use mechanical methods, such as space heating, dehumidification, and ventilation to dry wetted wood and speed up construction. This usually adds a considerable cost and may also bring other issues (e.g., a potential fire hazard). Aside from framing members that are typically covered after enclosure, appearance members often require costly remedial treatment to remove staining and to refinish after incidental wetting. Appropriate on-site protection can minimize or avoid all these unexpected construction needs and costs. This is particularly important for the construction of modern larger and taller wood buildings.

Checklists for the design and the construction stages are provided in Appendices I and II.

2 WOOD PRODUCTS AND ASSEMBLIES USED IN CONSTRUCTION

2.1 Products/Assemblies Classifications

Wood products and assemblies used in modern construction can be generally classified into the following groups and subgroups based on the characteristics of the materials including water absorption, entrapment, and drying potentials. They are listed below in order of the level of protection that may be required on construction sites, with Group A requiring the lowest level and Group D overall

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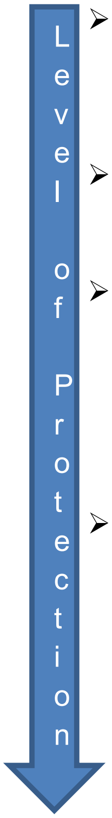
[1] More information on measuring moisture content is discussed in Section 2.3.

[2] Green wood is still used for wood construction in some areas of North America, such as California.

requiring the highest level of on-site protection. In addition to the wood material itself, the layout of the assemblies and type of materials surrounding the wood also have an impact on the drying performance, which are often taken into considerations during the design. The design aspect is not the focus of this document although it plays an important role on wetting risk and drying performance.

Level of protection by groups of wood products/assemblies:



- ***Group A: Solid wood***
    1. Group A1: Dimension lumber, typically 38 mm in thickness
    2. Group A2: Solid-sawn timbers, such as Douglas fir, eastern white pine, and western hemlock posts and beams, typically 114 mm or more in its smallest dimension
- ***Group B: Glue-laminated solid wood products***
    3. Group B1: Glued-laminated timber (glulam)
    4. Group B2: Cross-laminated timber (CLT)
- ***Group C: Wood-based composite products***
    5. Group C1: Traditional sheathing panels, such as plywood, oriented strand board (OSB), and fiberboard, typically with a thickness below 19 mm
    6. Group C2: Large structural composite (SCL) products, such as parallel strand lumber (PSL), laminated strand lumber (LSL), oriented strand lumber (OSL), and laminated veneer lumber (LVL)
- ***Group D: Prefabricated products/assemblies***
    7. Group D1: Prefabricated light wood framing primarily using dimension lumber and sheathing panels
    8. Group D2: Large built-up members: nail-laminated timbers (NLTs) built with dimension lumber and structural sheathing (i.e., plywood, OSB), typically used as floor/roof decks or elevator shafts (StructureCraft 2015)
    9. Group D3: Prefabricated closed assemblies, i.e., modular home assemblies, which integrate insulation, membranes, and other materials

2.2 Moisture Content at Manufacture

Wood products have different MC specifications at the time of manufacture. In North America, structural dimension lumber, such as Spruce-Pine-Fir (S-P-F), Douglas Fir-Larch (D. Fir-L), and 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% (additional moisture above approximately this MC level does not cause further expansion of the wood; see Section 3.1). 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.

The manufacture of engineered wood products has more strict moisture control requirements for achieving proper adhesive bonding to target a narrower range of strength properties. Consequently, engineered wood products are manufactured to have lower and more consistent MC than dimension lumber and solid-sawn timbers. Glue-laminated solid wood products, including glulam and CLT panels, are manufactured at MC levels from 11% to 15%. Wood-based composite products, such as plywood, OSB, LVL, LSL, OSL, and PSL, are manufactured with MC levels lower than or close to the indoor 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.

Prefabrication of the framing alone, or of closed assemblies including insulation, membranes, and other materials, also has more consistent control over wood MC under sheltered or conditioned environments. The wood typically has a MC below 15%; lower MCs, such as 12%, may be achieved when specified.

Figure 2 Prefabrication of building assemblies in a factory

Table 1 lists typical MC ranges at the time of manufacture. ***However, it must be recognized that there is no assurance that the MC of wood will not rise or fall 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. However, the MC of wood, particularly composite products, will usually increase resulting from short-term exposure to liquid water during construction, or more commonly, higher humidity than that during manufacturing. In order to fully benefit from using dried products, care must be taken to prevent them from wetting during shipping, storage, and construction.

Table 1 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 solid wood products, such as glued-laminated timber (glulam) and cross-laminated timber (CLT)	11-15%
C1	Sheathing panels, such as plywood, OSB, fiberboard	6-12%
C2	Large 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*	Large built-up members: Nail-laminated timbers (NLTs)	6-19%
D3*	Prefabricated closed assemblies	6-19%

* The dimension lumber usually has a higher MC than the sheathing panels. A lower MC for dimension lumber, such as 12%, can be achieved when prefabricated in a factory.

2.3 On-Site Moisture Content Measurement

The MC of wood should be measured and monitored on a construction site to help make informed decisions about protection, drying, and other needs. The MC of solid wood members can be measured by using a portable moisture meter typically based on electrical resistance (e.g., moisture sensor pins) or capacitance. The measurement should be conducted away from wood defects, such as knots and pitch pockets. Most resistance-based meters require the two pins to be inserted parallel to the grain. When the metal pins are not coated, i.e., non-insulated, they provide the highest MC reading of the wood between the two pins. When the pins are coated with a non-conducting material except at the tips, i.e., insulated, they measure the MC between the two tips and thereby may provide moisture readings at specific locations inside the wood (Figure 3, right)[3]. Such functions can be important to detect moisture entrapped inside a member or an assembly. A capacitance-based meter covers a large volume of wood, typically an area about equal to the meter’s footprint to a depth of about 25 mm. It is usually quicker and easier to use on a construction site (Figure 3, left). It also has the advantage of not leaving pin holes in the wood. When properly calibrated, both types of moisture meters have a working range from 6% to 25%, with errors approximately ± 2%. Some meters can provide higher readings, for example, 40-50%, with reduced accuracy. When conditions allow, the measurement should be adjusted for the effects of wood species and temperature. Comprehensive information about MC measurement is available in literature (James 1988; Garrahan 1988; Forintek Canada Corp. 2001; Onysko *et al.* 2010; FPL 2010; ASTM 2013). Note that special consideration and calibrations are required for measuring MC of wood-based composites, such as plywood and OSB, as well as treated

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[3] Internal MC measurement may be particularly important when monitoring a member that was severely wetted to the core (or originally manufactured green) and is currently drying. In this case, the MC varies from the core to the surface and a measurement with an insulated pin except at the tip can provide a good estimate of the average.

wood (e.g. preservatives- or fire retardant-treated wood), due to effects of the chemicals on electrical conductivity or capacitance (Forintek Canada Corp. 2001; Onysko *et al.* 2010).

Figure 3 Measuring wood moisture content using a capacitance-based meter (left) and a resistance-based meter (right)

3 RELATED FUNDAMENTALS

3.1 Wood and Moisture

Moisture exists in wood either as bound water (i.e., hygroscopic water) that is held within the cell walls or as free water (i.e., capillary water) that is stored in the cell cavities. As freshly cut (green) wood 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 averages about 30% among different wood species (FPL 2010), and 28% is commonly used for design-related calculations (CWC 2005). 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 properties, and MC. These properties only change with the change of the amount of bound water in cell walls.

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 relative humidity (RH) drops as the temperature increases with other factors remaining the same in a given environment. Wood dries 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 the water vapour in the air are called sorption, including both desorption, i.e., loss of bound water (causing shrinkage), and adsorption, i.e., gain of bound water (causing swelling). ***The moisture in the air does not introduce liquid water and will not increase the MC of wood above 30% (i.e., fibre saturation point), unless vapour condenses on the wood surfaces under extreme conditions and the wood is exposed to the condensed 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). In practice wood never reaches an EMC under the fluctuating environmental conditions encountered in construction. However, because wood gains and loses moisture slowly, 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 4 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 and can be neglected for practical purposes. Figure 4 also includes the EMC of OSB, plywood, and a type of low-density fibreboard (with data based on Kumaran 2002). Wood-based composites (e.g., OSB) often 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, Table 2 provides typical MC ranges under outdoor sheltered or indoor environmental conditions in different climates in Canada (excerpted from CWC 2005, Table 5.3). However, when wood is exposed on a construction site, liquid water sources (e.g., rain, snow, vapour condensation) usually play a more controlling role in the performance than sorption alone. See Section 4.1 and 4.2 for detailed discussions.

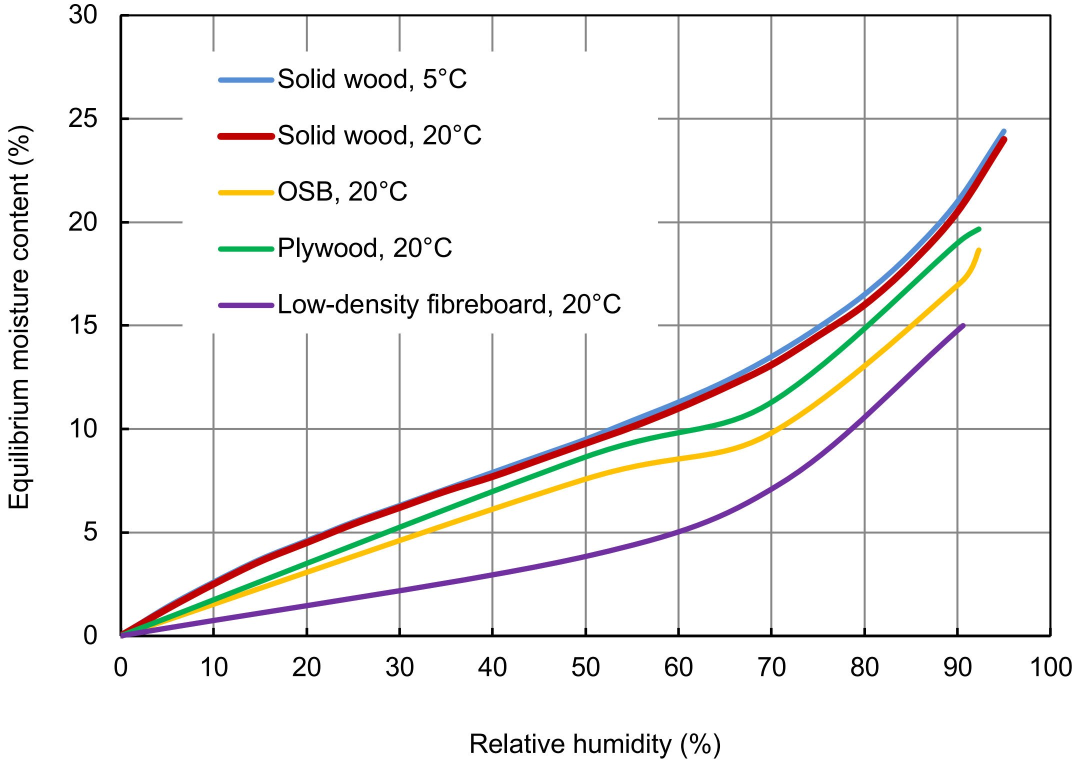

Figure 4 Representative isothermal sorption curves: equilibrium moisture content of solid wood and wood-based composites at various relative humidity levels (data sources: FPL 2010; Kumaran 2002)

Table 2 Typical equilibrium moisture content ranges of wood materials in different climates (excerpted from CWC 2005, Table 5.3)

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

3.2 Durability: How Much Moisture is Too Much?

Durability of wood components in this context primarily means resistance to fungi, such as staining, mould, and decay fungi. The most important conditions for fungi to grow in wood are suitable moisture and temperature conditions (Morris 1998; FPL 2010). ***Preventing extended exposure to moisture is the key to preventing most durability issues throughout construction and service life.*** The most serious bio-deterioration, decay, affects strength. It generally requires wood cell walls full of bound water and some free water inside wood cell lumens. The 19% rule was introduced at a time when most construction used green lumber and was based, in part, on data showing that when green lumber was infected with decay fungi in the standing tree, during harvesting, transport, or storage, the wood had to be dried to below 20% to stop decay. That is because decay fungi produce water as part of the decay process. When lumber is kiln-dried or logs are manufactured into engineered wood products, the heat involved kills any fungus present. The MC of KD lumber and EWP needs to rise to approximately 26% for decay fungi to infect and for decay to begin; it then takes months for detectable structural damage to occur under marginal conditions (Wang *et al.* 2010). However, when there is a larger amount of free water available with a MC ranging from 40% to 80%, decay and consequent strength loss can occur rapidly (e.g., in weeks in susceptible wood species). Compared with decay, mould or staining does not affect wood strength. Mould growth is more associated with the RH of the environment, more specifically, the surface RH (sometimes called “water activity”) of the building components. It needs a minimum surface RH around 80% to grow on wood at a temperature of 20-25°C; under such marginal conditions, it could take months or longer for mould to initiate on non-resistant wood materials (Nielsen *et al.* 2004). Incidents of mould growth or other types of fungal staining occurring during construction are more often associated with wetting caused by liquid water sources (e.g., rain, vapour condensation). Aside from fungi, discolouration can also be caused by metals, in combination with moisture, such as iron staining (Figure 5). For appearance products and exposed members, discolouration is often a major concern resulting from incidental wetting and often requires costly remediation treatment.

Figure 5 Iron staining on glulam

Under the same external conditions, different types of wood have different inherent resistance against mould or decay, primarily due to extractives in the wood. Sapwood is the newer part of a tree, closer to the bark (See Figure 6). 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). Relative to 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 western red cedar and yellow cedar has high natural resistance to decay. 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 mouldicides or preservatives, to improve its durability against mould or decay. More information about natural durability and preservative treatment can be found at www.durable-wood.com.

Sapwood is typically lighter in colour, more absorptive, and less durable than the heartwood in most wood species

Heartwood is typically darker in colour, less absorptive, and more durable than the sapwood in most wood species

Sapwood is typically lighter in colour, more absorptive, and less durable than the heartwood in most wood species

Figure 6 Sapwood and heartwood in a piece of Douglas fir lumber (left: end grain; right: tangential surface)

In addition to the effects of chemical compositions, inherent moisture-related properties, such as water vapour sorption and liquid water absorption, affect the durability. Water is also never uniformly distributed throughout a piece of wood. For example, the sapwood of most species is relatively more absorptive than the heartwood. The locations which tend to get in contact with and trap liquid water, and reach and retain a MC close to or higher than 30%, such as end grains and various joints, typically start to deteriorate sooner, especially under warm conditions. See further information about potential impacts of wetting on performance of wood construction in Wang (2016a).

4 WETTING AND DRYING POTENTIALS

The highest priority for wood protection at a construction site is to reduce wetting; re-drying may become necessary or a priority after wetting has occurred. Table 3 generally summarizes the wetting and drying potentials, appearance deterioration potential, and recommendations for protection for the different categories of wood materials/assemblies described in Section 2.1. As discussed in detail below, the nature of the materials used and how they are built into assemblies both play a role in determining the wetting (i.e., water absorption and entrapment) and drying properties (Sections 4.1 and 4.2). This may consequently dictate different levels of protection on site (Sections 5.1 and 5.2), when the drying performance, potential remediation needs and costs are also taken into account. In the other extreme, for materials which are highly susceptible to checking, cupping, and warping in a dry climate, measures may be necessary to increase the humidity level during construction or in service to slow down or to prevent excessive drying (Section 5.3).

Table 3 Wetting and drying potentials under typical construction conditions

Group	Subgroup	Examples	Water absorption/ entrapment potential	Appearance deterioration potential	Drying potential	Protection recommendations
A, Solid wood	A1, Dimension lumber	"S-Dry" S-P-F	Low	Low. Will typically be enclosed	Fast after surface wetting	Basic measures
	A2, Solid-sawn timbers	Unfinished Douglas-fir balcony posts	Low	Low. Will typically be covered or finished	Fast after surface wetting, but slow from green timbers, or after deep wetting, or after enclosure	Basic measures, e.g., keeping them away from liquid water and providing good ventilation
B, Glue-laminated	B1, Glue-laminated timber	Douglas glulam	Medium. It will increase if there are absorptive mechanisms (e.g., gaps and sapwood) inside.	Medium for unfinished but very high for finished members	Fast after surface wetting but slow after deep wetting or enclosure	From basic measures to more advanced measures. For coated members, the priming coat should be pre-applied in the factory, but the top coat should be applied at the site to reduce damage.
	B2, Cross-laminated timber	S-P-F CLT				
C, Composites	C1, Traditional sheathing panels	Plywood, OSB	Very high absorption	Low. Will be enclosed	Medium	Basic measures, e.g., edge sealing, keeping them away from liquid water and providing good ventilation
	C2, Structural composite products	PSL, LSL, OSL, LVL	High absorption potential	Very high for finished members	Fast after surface wetting but very slow after deep wetting or enclosure	Advanced measures, such as pre-installing membrane or using a temporary roof. Choose dry weather for installation.

D, Prefabricated	D1, Prefabricated light wood framing	Pre-framed wall, floor and roof without insulation etc.	From low to high. Joints can trap moisture.	Low. Will be enclosed	Medium. Fast after surface wetting but slow after deep wetting or enclosure	Basic measures, e.g., keeping them away from liquid water and providing good ventilation
	D2, Built-up members	Nail-laminated timber floors /roofs, double-layer plywood decks	Very high moisture entrapment potential	Very high for finished members	Fast after surface wetting but very slow after deep wetting or enclosure	Advanced measures, such as pre-installing membrane or using a temporary roof. Choose dry weather for installation.
	D3, Closed assemblies	Prefabricated closed walls and floors	Typically low, if all joints are sealed properly; but very high for unsealed joints	Very high for finished components	Slow. Will require opening assemblies to dry wetted materials	It depends on the assemblies and wetting potentials. Choose dry weather for installation.

4.1 External and Internal Factors Affecting Wetting and Drying

Wetting in this context results from exposure to liquid water, such as rain and snow (i.e., once melted) during construction. 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). The rainy winter climates in coastal areas, with long periods of rainy days, impose very large moisture loads on materials and assemblies exposed on site. Associated with weather conditions, the orientation and location of components also have a large effect. 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 to dry once the wetted wood members are covered with roofing materials, which typically have low vapour permeance (Wang 2014; 2016b). By comparison, vertical components, such as wall sheathing, typically receive smaller amounts of rain (mostly wind-driven rain) and can also dry relatively quickly. Components on ground are typically subjected to severe wetting resulting from exposure to standing water and other ground moisture. 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 is to remove snow from wood before it melts. In terms of drying, factors including RH and ventilation rates are very important.

Different materials/assemblies absorb and trap water, as well as dry at different rates (Wang 2014; 2015a; 2016b). The speed of absorption, depth of water penetration, and the amount of moisture retained during exposure to rain and other water sources largely depend on inherent factors, such as method of manufacturing; wood species; presence of internal voids; exposure of end grain; adhesive and wax contents for composite materials; and, if applicable, surface treatment. All these factors can affect the resistance to water absorption at surfaces and the resistance to moisture movement and distribution internally.

The major factors increasing the likelihood for moisture to penetrate deep in wood components, reducing the drying rate, and consequently leading to potential decay and other issues include:

- End grains, which are much more absorptive than other wood surfaces, exposed on tops of vertical components, ends of horizontal components, or embedded into or in direct contact with ground, concrete, or masonry that will stay damp
- Small gaps between members (e.g. a built-up member) that permit capillary moisture entrapment but limit air flow. It was found that gaps larger than 5 mm resulted in improved drying over trapping moisture for horizontal joists made with Norway spruce (Fredriksson *et al.* 2013).
- Combination of end grains and small gaps at joints
- Interconnecting voids and gaps within engineered wood products, particularly when the more absorptive sapwood (compared to heartwood) is adjacent to voids and gaps
- Being a large size or massive
- Large metal-plate connectors on the exterior

- Delamination in engineered wood products due to shrinkage and other issues
- Checking in sawn timbers and, to a lesser extent, in glulam and other products, particularly on horizontal surfaces (but downward facing checks on sides can also trap water)
- A wet member covered by materials with low vapour permeance, such as low-permeance membranes and insulation products (e.g., closed-cell spray foam, extruded polystyrene)

For any wood species and products, the drying rates generally occur at a lower order of magnitude than wetting rates, even under warm, dry, and ventilated conditions. Moreover, modern construction schedules may not provide sufficient time for drying, especially when combined with weather conditions that are not favourable for water evaporation. Large dimension members and built-up assemblies often have high wetting and low drying potential once water is allowed to penetrate deeply (see Section 4.2). End grains and small gaps in a member (e.g., CLT, NLT) or a joint also deserve special attention. In addition to material selection and on-site protection, the assemblies must be designed to dry inward, outward, or both inward and outward, in case wetting occurs during construction or in service. This can be achieved, for example, by using vapour-permeable materials (e.g., insulation, membrane) and integrating exterior or interior ventilation functions (e.g., a rainscreen cavity) (HPO 2016; Finch *et al.* 2013).

4.2 Wetting and Drying Potentials of Different Categories of Wood

Group A1, Dimension lumber of Canadian softwood species, such as S-P-F, D. Fir-L, and Hem-Fir, generally have a higher resistance to water absorption and penetration than the more permeable pines, such as southern pines and radiata pine (typically with wider sapwood), or the more permeable hardwood species, such as aspen and birch. Based on the experience with pressure preservative treatment, water does not penetrate lumber of refractory species, such as S-P-F and Douglas fir, 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 long exposure time (e.g., weeks) will lead to deep wetting and large amounts of water absorbed. The blue-stained sapwood of beetle-killed lodgepole pine typically has increased water permeability (McFarling *et al.* 2006). It was reported that the average MC of dimension lumber (studs and bottom plates, “S-Dry”) was about 20% during wood-frame construction in winter in Coastal British Columbia, before it was sheltered and heated for drying (Wang *et al.* 2013). However, there was a wide range in MC depending on exposure degrees, with some higher readings above 30%. By comparison, the average MC of lumber was lower, 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; Wang 2016c).

Group A2, Solid-sawn timbers, are similar to dimension lumber (Group A1) in terms of wetting and drying potentials for the same material, but with additional influence from the larger dimensions. When dry products are exposed to water for long periods of time (e.g., weeks), water penetrates deep into the wood, with consequently slow drying.

Groups B, C, and D, i.e., glue-laminated, structural composite, build-up, or prefabricated products/assemblies, generally have many advantages for industrial and commercial construction. For example, big members are readily available, or can be conveniently assembled for large spans. However, those products/assemblies often require special care during storage, transportation, and construction to prevent structural damage and other potential issues, such as excessive wetting, slow drying, and discolouration, compared with dimension lumber and solid-sawn timbers.

Group B1 and B2, glue-laminated solid wood products (e.g., glulam, CLT) made with Canadian softwood species generally exhibit the similarly low wetting potential as Group A products (McClung *et al.* 2014; Wang 2014; 2016b). When glulam and CLTs are installed as appearance members, incidental wetting often causes discolouration, particularly in association with iron staining and requires remedial work (e.g., sanding and refinishing). Small gaps between boards of a CLT panel may increase water uptake and entrapment resulting from capillary effects. Edge-gluing the boards, particularly on the faces of a CLT panel, can increase water resistance as well as airtightness; however, this may result in more random checks after drying. Measures should be taken to avoid long periods of wetting (e.g., weeks), and use of low-permeance materials (e.g., insulation, membrane) should be minimized in the building envelope assemblies.

Group C, wood-based composite products, generally have more micro-voids and increased amounts of end grain that can make these products more susceptible to deep wetting, compared with solid wood products. But the presence of adhesive and wax, if any, may considerably reduce water absorption. The dimension and exposure are also important factors. For example, plywood and OSB (Group C1) can be saturated with water more easily compared to thicker products; however, the thinner panels of plywood and OSB also dry more quickly when conditions allow (Wang 2014; 2016b). This is the main reason that it is usually not a major concern to see wet plywood or OSB in light wood-frame construction. However, drying of large structural composite products (Group C2) can be a large concern and incur high cost. In addition, when large members are exposed for aesthetic appearance, staining resulting from incidental wetting usually requires refinishing. Preventing wetting is therefore critically important for large structural composite products.

Group D, prefabricated products/assemblies are unique in terms of wetting and drying potentials. Prefabricated light wood framing of walls and floors (***Group D1***), typically built with dimension lumber and sheathing panels, is commonly used for mid-rise wood-frame construction (e.g., 5- and 6-storey buildings, Figure 7). This is a great step above the traditional stick-built construction to improve construction efficiency. Forced drying is effective to dry wetted framing and often used before enclosure in a cold and wet climate.

Group D2, large built-up members, such as NLTs built with dimension lumber (often with structural sheathing, pre-installed or not), or built with double or more layers of plywood (or other panels), can be susceptible to excessive wetting. Water gets trapped easily between the boards or panels and will be very slow to dissipate, even under heated conditions (Wang 2014; 2016b). Consequently, fungal growth can start quickly in those risky locations. Such products/assemblies must therefore be carefully protected against rain during construction (Sections 5.1 and 5.2). Special attention should also be paid in design to promote drying of the final assemblies.

Group D3, prefabricated closed assemblies (e.g., modular homes) offer many advantages for construction and on-site moisture management (Figure 8). Prefabrication, which can be carried out in a simple shelter or well-conditioned factory environments, should be used whenever possible to improve construction efficiency and reduce exposure time. However, when the prefabrication includes materials, such as insulation and membranes, but is not made completely tight against moisture penetration, the materials other than the wood will have a large effect. Most insulation and membrane products, such as closed-cell spray foam, extruded polystyrene, polyethylene, and self-adhesive membrane have low vapour permeance and will greatly reduce the drying rates. It usually becomes complicated and expensive to open the assemblies and dry the materials before re-enclosure, once wetting occurs. Additional remedial treatments or replacements may also be necessary if mould growth has started or finishing material has discoloured.

Figure 7 Using prefabricated framing for multi-unit light wood-frame construction

Figure 8 Installing a modular roof on a house

5 ON-SITE PROTECTION

5.1 Overall Protection Strategies and Methods

The wetting and durability risk, protection needs, and costing for different levels of on-site protection as well as potential remediation should be assessed to make informed decisions based on the materials/assemblies used (see Table 3), climatic conditions during construction, and the final assemblies. Standards related to on-site moisture management and other aspects of quality assurance have been developed in countries, such as Finland (Finnish Standards Association 2012). The Finnish standard requires that the construction company develop a moisture control plan and an assembly plan for wood materials used for load-bearing structures in coordination with manufacturers and designers. Both plans should include the expected level of on-site protection based on the design MC of wood. That includes, if the target MC is below 15% (which would include almost all wood elements in a conditioned indoor space), that the expected protection level would be Protection Level 3 (PL3). PL3 requires indoor conditions or a heated tent for construction.

In the North American context, there is no regulatory requirement for on-site moisture management. The following basic storage or temporary protection measures should be taken into consideration in any type of wood construction:

- Using prefabrication as much as possible to reduce on-site exposure time
- Scheduling framing and enclosure in a drier season, whenever possible
- Coordinating material delivery for just-in-time installation to reduce on-site exposure time
- Keeping materials away from ground by placing them on dunnage with sufficient clearance to permit airflow under the packages
- Storing materials in well-ventilated shelters
- End-sealing exposed end grains of wood members, such as by using a water repellent or a primer
- Using wraps and tarps to prevent rain ingress during storage and construction (see an example in Figure 9); however, taking measures to accelerate drying once moisture gets inside

Figure 9 Covered prefabricated framing at a construction site

More advanced protection methods should be considered for materials and assemblies that are highly susceptible to wetting and very slow in drying, and/or will require costly remedial treatments once wetting occurs (e.g., Groups B2, C2 and D2). Although such a protection method typically requires more work and is more expensive, the effort may result in savings in time and costs elsewhere. Examples include:

- Purposely utilizing the shell of a building (e.g., floors, roof, walls) for protection, such as through sealing all joints by taping to protect the elements inside
- Pre-installing temporary or permanent protective membranes on members or on assemblies
- Using a temporary roof for partial or the entire construction (an example shown in Figure 10)

Figure 10 Using a tent to protect roof construction in a recent Vancouver project

5.2 On-site Protection Considerations for Different Categories of Wood

“S-Dry” lumber (***Group A1***) and engineered wood products (***Groups B and C***) are typically covered with wraps when the packages arrive at a site. The packages should ideally be kept in a shelter, using dunnage below to keep the wood off the ground. The wraps should be kept until the products are ready for installation. When a wrap is opened, the cutting should prevent rain penetration but encourage drainage and drying (e.g., by cutting the wrap underneath), and the wood should be re-covered with waterproof tarps whenever possible. The wraps and tarps used for on-site protection should be breathable to allow drying; plastic wraps or tarps may trap moisture and slow down drying once water gets inside. Inspect stored materials regularly. Some engineered wood products, such as glulam beams, should be placed at the site based on their final positions in the building. Any wet material should be properly stacked and kept under covered and ventilated conditions to accelerate drying. Wood-based composite materials (***Group C***), large structural composite products (***Group C2***) in particular, typically require more attention during storage and handling than solid wood products. When solid-sawn timbers (***Group A2***) arrive at the site with a high MC, they generally require good ventilation for drying while being kept away from water sources.

When an aesthetic coating is used on a large wood member such as glulam, the priming coat should be pre-applied in the factory to serve as a temporary on-site protection, but the top coat is recommended to be applied at the site to reduce damage during construction. Factory finishing with a water repellent or a primer can be particularly beneficial for an end-grain or other surfaces, which are more likely to be temporarily exposed to liquid water sources during construction. The treatment can make the wood surfaces water-repellent and reduce water absorption within a short period of exposure. If a treatment makes the wood slippery, it should be avoided on surfaces where there will be foot traffic during construction (e.g., subflooring, roof sheathing).

For a NLT deck (***Group D2***), the sheathing on the top (typically plywood) needed to meet structural requirements should use tongue-and-groove panels and be pre-installed in the factory to reduce the amount of water that can reach and get trapped between the boards (Wang 2016b). There are areas where the sheathing connects adjacent NLTs and can only be installed at the site. These areas should be kept to a minimum and the sheathing should be installed as soon as the construction allows. It should also be coordinated to install the prefabricated assemblies under dry weather conditions and then they should be protected using plastic tarps until they are completely closed in.

The upper surface of a large horizontal member or a panel of a floor or a roof (***Groups B1, B2, C1, C2, D1, D2***) may have a protective membrane (e.g. a plastic or fabric-type membrane, preferably self-adhered or liquid-applied when suitable) pre-applied before installation (Wang 2016b). Any joints and interfaces should be immediately sealed once the members or panels are installed to prevent rain and meltwater from seeping through the gaps and getting trapped within the wood members. This membrane should resist wear and tear and remain water resistant for the duration of construction. Ideally the selected protective membrane will serve permanently as part of the designed assembly. For example, for a roof it can be co-ordinated to pre-install part of the selected roofing membrane, which is typically thick, heavy-duty, and has a very low vapour permeance. The membrane has to be removed to accelerate drying if wetting occurs; however, it may not be easy to remove a self-adhered membrane. A floor assembly or an elevator shaft, which is located in an indoor environment once the building is completed, does not need a water-resistive membrane in the final assembly. But a thin and strong membrane, ideally highly vapour permeable, may be installed to serve as a protective membrane for construction. This membrane, if it is not self-adhered, can be removed once the floor or elevator shaft is sheltered; or simply retained, particularly when concrete topping will be installed on the floor. Note that the vapour-permeable building paper and plastic housewrap products commonly used in exterior walls are not able to prevent water ingress from a horizontal surface for a long exposure time (Wang 2016b).

In a wet climate, a temporary roof may be installed to shelter the construction of materials and assemblies, which are highly susceptible to water uptake and are very slow in drying, or highly susceptible to staining and would require costly remedial treatments (***e.g., Groups B2, C2 and D2***). Such weather protection is common in the repair and retrofit of existing buildings to maintain normal living conditions (see an example in Figure 11). It would also be very beneficial in new construction if the budget allows. Fixed tents, similar to those used in retrofits, can be built with scaffoldings and tarps to protect roof and cladding installation (Figure 10, Figure 12). Movable tents, which are raised as each storey is built, have been used in large timber projects in Europe (see an example in Figure 13).

Compared to a fixed tent, a movable roof has more stringent structural and mechanical requirements and therefore costs much more. The cost of installing a temporary roof for on-site protection may be offset by prevention of time loss, increased construction efficiency, and elimination of re-drying and other remedial treatments resulting from on-site wetting. Such a method should be compared with other measures (e.g., pre-applying membranes) to identify the most effective and economical on-site protection.

Figure 11 Weather protection using a fixed temporary roof during retrofit of a building in Vancouver

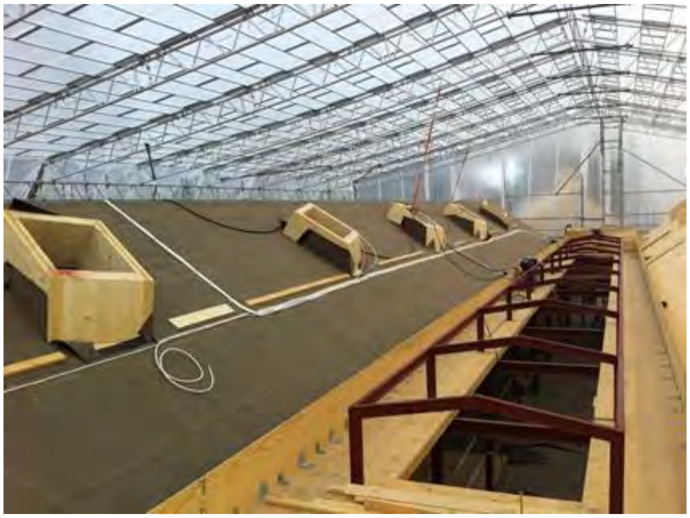

Figure 12 Using a fixed temporary roof to protect roof construction in Norway (Photo courtesy of Fristad Bygg)

Figure 13 Using a movable temporary roof to protect the entire construction in Sweden

Prefabrication (***Groups D***) is strongly recommended for the construction of large and tall wood buildings to reduce on-site exposure time. The prefabrication plan, however, must be carefully reviewed to identify potential wetting risks. For prefabricated light wood framing (***Group D1***), attention may be needed for components and joints that may trap moisture, such as the joints between bottom plates and subflooring (therefore standing water on subflooring should be removed to reduce water entrapment). In most cases, protective or permanent membranes can be installed for a wall or a roof during prefabrication to increase construction efficiency and to provide extra protection to the framing inside. Attention should also be paid during the design of assemblies (e.g., the design of various joints) and factory assembling to facilitate on-site installation and to prevent rain ingress during transportation and construction. This is particularly important for modular home installation when all materials are prefabricated into the assemblies (***Group D3***).

The shell of a building often provides an effective and economical shelter for the wood inside and should be taken full advantage of during construction. This typically requires good sequencing and coordination. For example, an upper floor or a roof usually provides good protection to the floors and other components below, particularly when the joints and gaps in the sheathing are sealed right after installation, such as through use of tongue and groove sheathing panels, and ideally taping. Any standing water (or snow) should be removed from a horizontal surface after a large precipitation event. When the wood is dry enough, install the roof sheathing and waterproofing membranes and the exterior wall weather resistive barriers 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 those for skylights, windows and doors, should be temporarily covered with translucent membranes (for providing natural light) to prevent blown-in rain or snow before enclosure. Wet services, such as concrete elevator shafts and concrete topping on subflooring or on a roof, should be completed at early stages to minimize adverse impacts on the wood. Insulation materials and membranes, particularly spray foam and self-adhesive membranes, should not be applied on wet wood. Walls, roofs, and any other parts must not be closed in and finished until the framing materials have dried to an acceptable level of moisture, i.e., typically below 19%. When a roof built with mass timbers is exposed to wetting, measures should be taken to dry them before installing thermal insulation or water proofing membranes above. It is very difficult and slow for moisture to move through a mass timber and to dry towards the interior once the roofing is installed. Mechanical methods, such as space heating, dehumidification, and forced ventilation, can be used to accelerate drying before enclosure. However, heating by using a fuel, such as natural gas or propane, will add to the wetting load due to the extra moisture generated during the burning and may also become a construction fire concern.

5.3 Protection in a Dry Climate

The on-site protection needs can be very different in a dry climate, compared to construction under wet weather conditions. Excessive checking, cupping, or warping resulting from rapid drying or cyclic wetting and drying, causing aesthetical and dimensional instability issues usually becomes the major concern (Wang 2016a). An effective measure is to avoid extremes in the environment through humidity control, typically humidification when it is too dry. The humidity should be measured during construction and a relatively closed space needs to be created to make the humidification effective and efficient. In addition to on-site moisture management, humidity control is typically required for mass timber buildings in a dry climate, especially in the first few years, to allow the wood to adjust to the service conditions slowly (Wang 2015b).

6 CONCLUDING REMARKS

In a wet climate, different products/assemblies require different levels of on-site protection to minimize water absorption and entrapment and to accelerate drying when wetting occurs. The amount of effort and the effectiveness of the methods will depend on the types of products/assemblies involved and other conditions. Building assemblies should always be designed to dry, in case wetting occurs during construction or in service. In the other extreme in a very dry climate, humidification may instead be used to slow down or to reduce wood drying in order to reduce checking, cupping, and warping.

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APPENDIX I: CHECKLIST FOR THE DESIGN STAGE

The following list of items should be checked for major materials and assemblies used for a large/tall building in the design phase. See the document for detailed information.

1. Is the building going to be built in a climate that rarely rains or snows?

   ☐ Yes. No need to proceed to the following check points
   ☐ No. Proceed to the next item

2. What are the major wood materials or built-up assemblies used? Check the document for their wetting, drying, and appearance deterioration potentials.

   ☐ Group A1: Dimension lumber
   ☐ Group A2: Solid-sawn timbers
   ☐ Group B1: Glued-laminated timber (glulam)
   ☐ Group B2: Cross-laminated timber (CLT)
   ☐ Group C1: Traditional sheathing panels, such as plywood, oriented strand board (OSB), and fiberboard
   ☐ Group C2: Large structural composite products, such as parallel strand lumber (PSL), laminated strand lumber (LSL), oriented strand lumber (OSL), and laminated veneer lumber (LVL)
   ☐ Group D1: Prefabricated light wood framing primarily using dimension lumber and sheathing panels
   ☐ Group D2: Large nail-laminated members built with lumber and plywood
   ☐ Group D3: Prefabricated closed assemblies, i.e., modular home assemblies
   ☐ Other

3. If at least one of the following items is checked, extra on-site protection should be considered, in addition to careful design to achieve good drying performance and to prevent wetting in service.

   ☐ The material or assembly absorbs water readily
   ☐ The material or joints/interfaces allow water to get in and trap moisture
   ☐ The material or assembly dries slowly once wetted
   ☐ The material or assembly, such as a roof deck, will be enclosed with material (e.g., membrane, insulation) with low vapour permeance
   ☐ Exposure to wetting during construction will require remediation treatments, such as removing staining on appearance products

4. Options for extra on-site protection measures and cost estimation, by working with the construction company.

   ☐ Sealing all wood surfaces, particularly end grains, by using a water repellent or a primer; cost assessed
   ☐ Purposely utilizing building shells for protection; cost assessed
   ☐ Pre-installing protective membrane on a member or on an assembly; cost assessed
   ☐ Using a fixed tent for partial protection of construction; cost assessed
   ☐ Using a movable protective roof which rises during construction; cost assessed

5. Specify a suitable protection strategy and methods to protect wood during construction.

APPENDIX II: CHECKLIST FOR THE CONSTRUCTION STAGE

The following list of items should be checked for each major construction procedure of a large/tall wood building project, in coordination with the design team and other trades involved.

1. Is the construction happening in a dry climate that rarely rains or snows?

   ☐ Yes. No need to proceed to the following check points
   ☐ No. Proceed to the next item

2. What are the major wood materials or built-up assemblies used? Check the document for their wetting, drying, and appearance deterioration potentials.

   ☐ Group A1: Dimension lumber
   ☐ Group A2: Solid-sawn timbers
   ☐ Group B1: Glued-laminated Timber (glulam)
   ☐ Group B2: Cross-laminated Timber (CLT)
   ☐ Group C1: Traditional sheathing panels, such as plywood, oriented strand board (OSB), and fiberboard
   ☐ Group C2: Large structural composite products, such as parallel strand lumber (PSL), laminated strand lumber (LSL), oriented strand lumber (OSL), and laminated veneer lumber (LVL)
   ☐ Group D1: Prefabricated light wood framing primarily using dimension lumber and sheathing panels
   ☐ Group D2: Large nail-laminated members built with lumber and plywood
   ☐ Group D3: Prefabricated closed assemblies, i.e., modular home assemblies

3. Does the material arrive on site with good wraps?

   ☐ No. Carefully covering it with tarps and storing it in a well-ventilated shelter. Check the stored material regularly for any wetting incidents.
   ☐ Yes. Avoiding damage to the wraps or moisture entrapment inside the wraps. Check stored material regularly for any wetting incidents.

4. Is the material or assembly in contact with the ground?

   ☐ Yes. Place the material or assembly on dunnage
   ☐ No. Proceed to the next item

5. Extra attention to site protection is required, if at least one of the following items is checked.

   ☐ The material or assembly absorbs water readily
   ☐ The material or joints/interfaces allow water to get in and trap moisture
   ☐ The material or assembly dries slowly once wetted
   ☐ The material or assembly, such as a roof deck, will be enclosed with material (e.g., membrane, insulation) with low vapour permeance
   ☐ Exposure to wetting during construction will require remediation, such as due to staining on appearance products

6. Assess options for extra on-site protection measures by working with the team.

   - ☐ Sealing wood surfaces, particularly end grains, by using a water repellent or a primer; cost assessed
   - ☐ Purposely utilizing building shells for protection; cost assessed
   - ☐ Pre-installing protective membrane on a member or on an assembly; cost assessed
   - ☐ Using a fixed tent for partial protection of construction; cost assessed
   - ☐ Using a movable protective roof which rises during construction; cost assessed

7. Is wood moisture content measured during construction?

   - ☐ Yes. Provide drying measures, such as space heating and forced ventilation, before enclosure, if the moisture content readings are repeatedly above 20%
   - ☐ No. Monitor wood MC at critical locations. Provide drying measures when needed.

8. Implement effective and cost-effective on-site protection

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