WETTING AND DRYING PERFORMANCE OF WOOD-BASED ASSEMBLIES RELATED TO ON-SITE MOISTURE MANAGEMENT

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ABSTRACT

On-site moisture management has become increasingly important for modern wood buildings with the increase in height and area, which potentially prolongs the exposure to inclement weather. There is also overall reduced drying ability in modern building assemblies, resulting from increased insulation levels, use of membrane and insulation with low vapour permeance, and use of wood members having high wetting but low drying potential.

This paper covers four different studies related to on-site moisture management. It first presents baseline moisture content (MC) measured from softwood dimensional lumber during construction of light wood-frame buildings in the coastal climate of British Columbia. When a building was framed in the winter, i.e., a wet season, the average MC was about 20%, with a wide range resulting from different degrees of exposure, before it was sheltered and heated for drying. By comparison, the average MC was lower, about 15%, with a much narrower range when framed in a warm and dry season.

It then covers laboratory testing to assess the wetting and drying potential of a range of wood-based roof / floor decks, including light wood frame (plywood and oriented strand board (OSB)), cross-laminated timber (CLT), and nail-laminated timber (NLT) assemblies for purposes of identifying needs for on-site protection and design for durability. For example, it was found that wet plywood, when sandwiched between low-permeance roofing membrane on the top and closed-cell spray foam underneath, could barely dry. For NLT, moisture got trapped between boards easily; the subsequent drying was slow even under space heating. In terms of potential protection measures, two types of vapour-permeable membranes showed limited moisture protection for NLT in horizontal applications.

A case study is last presented about MC measurements in the 18-storey mass timber building (Brock Commons) recently built at the University of British Columbia in the context of on-site moisture management. The CLT floors wet up slowly, and on-site measures should aim to reduce the time of exposure to rain.

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, and 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. Practices and regulations related to on-site moisture protection have been advanced in countries, such as Finland (Finnish Standards Association, 2012). The National Building Code of Canada (Part 9) requires that the MC of wood shall not be more than 19% at the time of installation (NRC, 2015). This is typically interpreted by practitioners to be the MC limit before enclosure. There is no other specific requirement for on-site moisture management[1]. This paper aims to assemble data to identify the needs for on-site moisture management for a range of wood-based assemblies and to shed light on effective and practical moisture protection measures based on related studies conducted by FPInnovations in the past years. Relevant to this paper, development of guidelines on on-site moisture protection of wood construction is also underway (Wang, 2016a).

MOISTURE CONTENT DURING CONSTRUCTION OF LIGHT WOOD-FRAME BUILDINGS

Moisture Content Measurement

The MC of wood, primarily dimensional lumber, was measured during the construction of three light wood-frame buildings in the coastal climate of British Columbia, covering both the winter (cold and damp) and the summer (warm and dry) seasons (Wang et al., 2013; Wang and Ni, 2014; Wang, 2016b). They were all built without measures purposely applied to reduce wetting of the framing. Building No. 1, a 4-storey building used local Spruce-Pine-Fir (S-P-F) dimensional lumber for all wall plates, studs, and floor joists. It was framed in a typical winter in this area and the wood was exposed to an excessive amount of rain. Building No. 2, a 5-storey building used S-P-F dimensional lumber for wall studs and Douglas-fir for wall plates. It was built in two phases, with Phase A framed in a wet season and Phase B framed under much warmer and drier weather conditions. Building No. 3, a 6-storey building was mostly framed over the summer of 2014 but its last framing stage was exposed to wet weather. Both Building No. 2 and No. 3 used similar materials including engineered wood floor joists.

The MC measurement in these three buildings aimed to provide baseline moisture information for assessing vertical movement (Wang, 2017) and also to identify on-site moisture protection needs. MC was measured during framing on random site visits using a hand-held capacitance-based moisture meter (Wagner Digital Recording Moisture Meter, Model L 610) to show general trends of MC changes during framing. The device measures average MC close to wood surface and has good accuracy for MC ranging from 6% to 25%. Occasionally the moisture meter showed readings around 34%, indicating that the MC was beyond the capacity of measurement. The measurements were randomly conducted on sill plates, bottom plates and studs of walls on each floor, with over 20 measurements for each category (e.g., the bottom plates on the 2nd floor). Wood-based composite elements including plywood, OSB, and structural composite lumber were not measured since calibration coefficients were not available. In addition, resistance-based moisture sensors were installed in a few locations in Buildings No. 2 and No. 3 to measure MC from construction to service.

[1] An ASHRAE guideline on construction moisture management is being developed.

Results and Discussion

When the buildings including Building No. 1 and Phase A of Building No. 2 were framed in wet weather, the MC readings measured from dimensional lumber elements did not exceed 30% often, without many intentional protection measures (Figure 1). There was a wide range in the readings resulting from varying degrees of exposure to rain. In general the upper floors had shorter time of exposure compared to the lower floors in each building. The wood members on the lower levels were reasonably protected by the upper floors / roofs, once installed. However, standing water on the concrete slabs greatly increased the exposure of sill plates and the bottom part of each stud to moisture. It was found that the average MC remained around 20% during framing under wet weather conditions before the roofs and exterior walls provided protection against rain penetration. It was therefore necessary to use forced drying, with space heating provided in these two buildings to dry wood quickly to achieve a MC below 19% before enclosure. By comparison, the need for moisture protection or forced drying greatly diminishes when the buildings including Phase B of Building No. 2 and Building No. 3 were framed in dry weather. The MC of most dimensional lumber stayed considerably below 19%, with an average MC of about 15% (Figure 2).

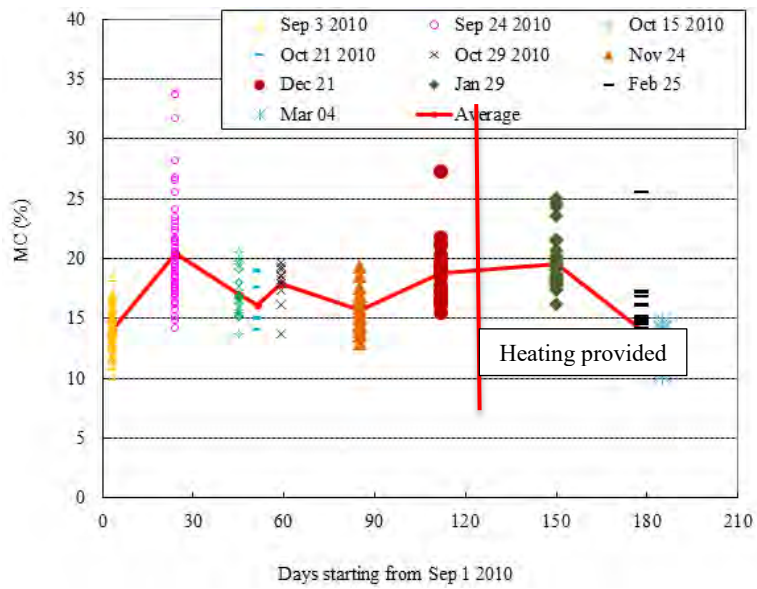

Figure 1: Changes of moisture content during construction, measured at chest height of wall studs on the 1st floor of Building No. 1, framed in wet weather

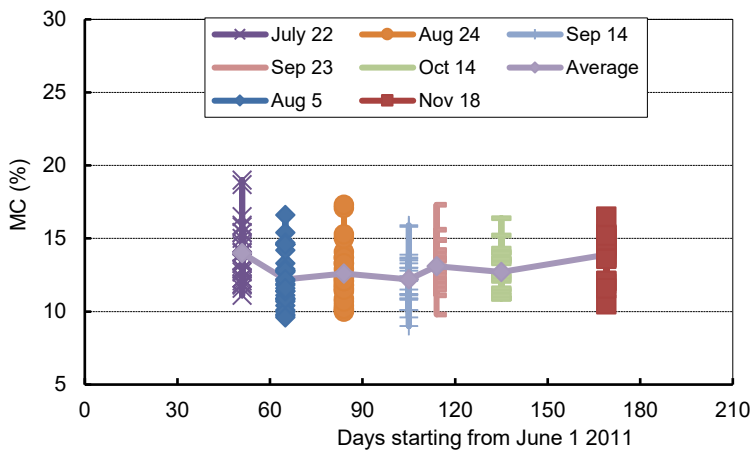

Figure 2: Changes in moisture content measured at chest height of wall studs on the 4th Floor during construction of Phase B of Building No. 2, framed in relatively dry weather

Related to this, the resistance-based moisture pins installed in Building No. 2 and No. 3 indicated that the MC of wood diminished slowly from construction into service. Using Building No. 3 as an example, the MC of the dimensional lumber members (sill plates, wall studs) on the first floor decreased from a range between 15% and 20% when the roof sheathing was installed, to a range from 8% to 15% half a year into service (Figure 3). The MC readings from the exterior wall were overall higher than those measured from the interior wall, and those measured from the sill plates were higher than those from chest height of the studs at each location. The measurement confirms that the final MC of dimensional lumber in service was around 8-9% in the heating season in this climate.

The MC of wood is partially reflected by the environmental conditions it is exposed to. Based on the measurements of relative humidity (RH) and temperature in Building No. 3, the service environments were similar between the exterior wall and the interior party wall in the summer (June-August, 2015, Figure 4**Error! Reference source not found.**). In the colder months of occupancy the interior wall was warmer and had greatly reduced RH due to space heating, compared to the exterior wall; in the same exterior wall, the RH on the exterior sheathing side was much higher than that on the interior drywall side. The RH adjacent to the plywood sheathing occasionally approached 80% in the winter of 2015, resulting from heavy influence of the exterior damp weather, typical of this climate. Wood would achieve an equilibrium moisture content of approximately 16% under constant environmental conditions at a RH of 80% and a temperature of 20°C (FPL, 2010).

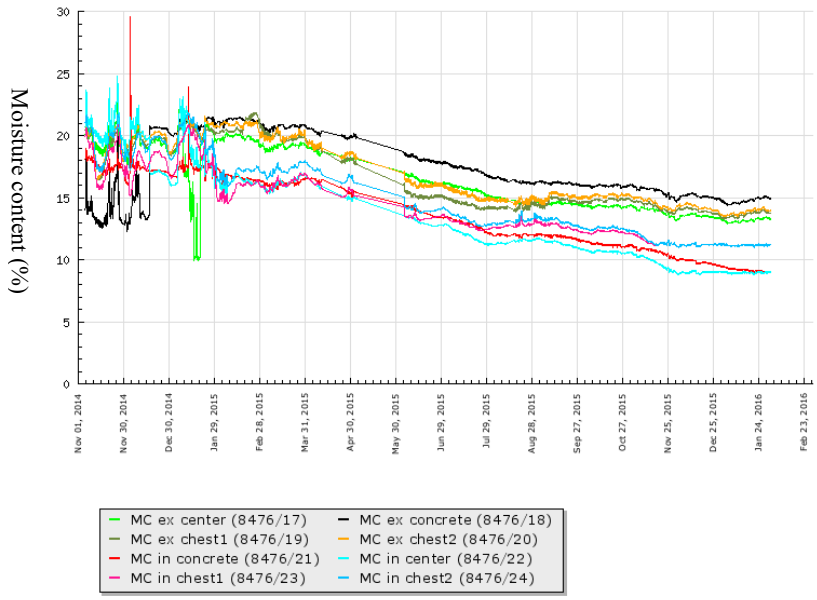

Figure 3: Moisture content measurements based on resistance-based sensors installed in the party wall and the exterior wall on the 1st floor of Building No. 3 for 15 months from construction to service

(Chart legends: "MC means "moisture content", "ex" means "exterior wall", "in" means "interior party wall", "concrete" means "being adjacent to the concrete curb", "center" means "in central sill plate", and "chest" means "at chest height of wall studs")

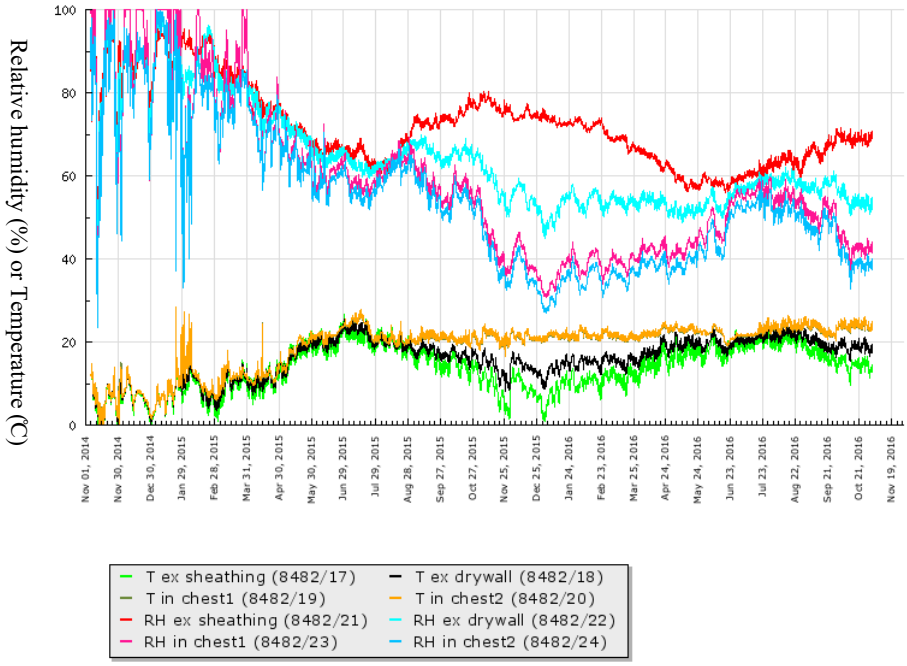

Figure 4: Temperature and relative humidity measured from the party wall and the exterior wall on the 1st floor of Building No. 3 for 24 months from construction to service

(Chart legends: "T" means "temperature", "RH" means "relative humidity", "ex" means "exterior wall", "in" means "interior party wall", "sheathing" means "adjacent to exterior plywood sheathing", "drywall" means "adjacent to interior drywall", and "chest" means "at chest height of wall studs")

LABORATORY ASSESSMENT FOR WETTING AND DRYING PERFORMANCE OF WOOD-BASED ASSEMBLIES

Roof Decks Based on Plywood, OSB, CLT, and LVL

Laboratory Assessment

Thin panels, such as plywood and OSB, are conventionally used in roofs or floor decks in North America. Mass timber systems based on CLT and laminated veneer lumber (LVL) etc. have been increasingly used, particularly in non-residential construction. Roof decks are typically subjected to a high moisture risk due to a high potential of wetting during installation and in service. Good drying capacity is therefore critically important as it may not always be practical to construct during dry weather.

In this study a range of small-scale roof assemblies were built using plywood, OSB, CLT, or LVL as the deck to assess differences in wetting and drying potentials (Wang, 2014). The plywood and OSB specimens used were roof sheathing products commonly used in larger buildings, both 19 mm in thickness. The CLT panels were made with 3-ply lumber and about 100 mm in thickness. The LVL was made with 13-ply veneer and about 40 mm thick. The major species was S-P-F except for OSB, which is typically made with aspen in North America. Most of the deck specimens were cut into dimensions of 300 mm × 300 mm, referred to as "small roof assemblies"; and some had dimensions of 900 mm × 1200 mm, referred to as "large roof assemblies". Each test panel was edge-sealed with epoxy and each test condition had 3 replicates.

Each deck specimen, edges sealed with epoxy, was wetted using controlled spray of water to simulate a severe wetting incident caused by rain on construction sites. The specimens were horizontally placed on shelves under spray nozzles in the laboratory. The environmental RH was controlled at 90% with a temperature of 20°C. The top surface of each deck was hourly sprayed with water for about 2 weeks, with each spray lasting 5 seconds. This wetting scheme was intended to simulate the frequent small rain events in the coastal climate of British Columbia, with an estimated precipitation of about 300 mm in total. Each deck specimen was then built into a roof assembly to test the drying rates. Most test assemblies had a single layer of deck, except for a few built with 2-layer plywood. Double layers of sheathing could be specified for structural requirements in building projects.

A self-adhered impermeable membrane, or standard 15-pound roofing felt plus asphalt shingles, simulating different roofing systems, was used to cover the wetted top surface of each deck specimen (Figure 5). Closed-cell spray foam insulation was applied underneath in several assemblies, simulating an interior insulation with low vapour permeance. Open-cell spray foam was applied in a few specimens as a reference of a more vapour-permeable interior insulation product. The assemblies with built-in moisture were subsequently exposed horizontally under different conditions to assess their drying rates. A larger group of test assemblies was exposed in a shed, which was covered but open to outside on one side, without solar exposure, mechanical ventilation, or space heating. This was used to simulate the condition of a newly built roof in this climate, when the roof deck was severely wetted during construction and subsequently covered with membranes, before space heating could be applied. The drying rates of most decks were assessed by periodically weighing each roof assembly, followed by calculating the average MC of each wood deck. A smaller group of large plywood specimens, covered with an impermeable membrane on the top, was each

installed above a plywood box, measuring 900 mm × 1200 mm × 1200 mm (height) located in the same shed. A small heater was placed in each box to maintain a temperature of around 20ºC, thereby creating a temperature differential across the roof assembly. This was used to assess the effect of a purposely created drying force, but under reversed temperature differential conditions. It was assumed by many practitioners that the impermeable roofing membrane above the plywood would prevent drying driven by such temperature gradients. Resistance-based moisture sensors were installed in each layer of the plywood sheathing to better assess drying performance. The moisture pins were insulated (coated) except at the tips with calibration based on lodgepole pine. In addition, reference specimens of plywood, OSB, CLT, and LVL without any covering material were exposed in the exterior to assess wetting and drying behaviour under exterior conditions in the winter.

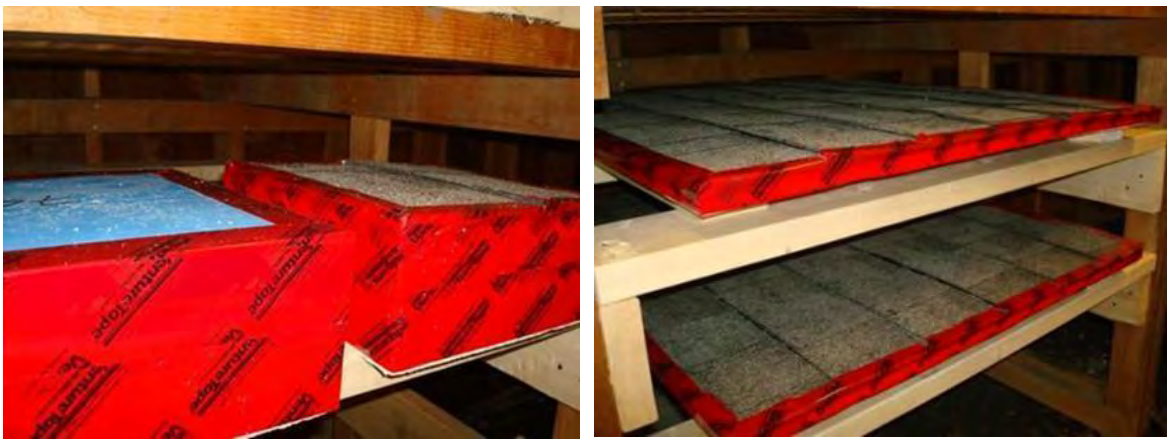

Figure 5: Left: Drying of small roof assemblies (covered with a self-adhered impermeable membrane or felt and asphalt shingles) on the shelves in the shed; Right: Drying of larger roof assemblies (covered with a self-adhered impermeable membrane or felt and asphalt shingles) in the same shed

Results and Discussion

Wetting Potential

Figure 6 shows the average MC of different deck materials before and after the laboratory wetting, and when appropriate, after 2 months of exposure in the exterior. The composite specimens including plywood, OSB, and LVL, all started with an initial MC of about 6% before wetting, and the CLT specimens started with an initial MC of about 12%. After the laboratory wetting for about 2 weeks, the small plywood specimens achieved the highest average MC among the materials tested, around 70%. It was followed by the small OSB specimens, with an average MC of about 60%. The large plywood specimens had a lower MC of about 54% possibly because the number of nozzles was not large enough to cover the entire surface during the wetting procedure. By comparison, the LVL specimens achieved an average MC of about 32% and the CLT specimens had the lowest average MC, about 25%. Note these MC values were all based on gravimetric measurements, without accounting for variations in moisture distribution in each panel specimen.

The controlled laboratory wetting scheme was partially justified by the comparable MC achieved by the

same deck materials after 2 months of natural exposure in a wet season in this climate. There were about 36 days with precipitation above 0.2 mm, in a total precipitation amount of 190 mm during the period of natural exposure. The amount of moisture absorbed and kept for a given material depends on external factors, such as the frequency of wetting (e.g., rainy days), amount of water (e.g., precipitation), humidity levels, solar radiations, and other environmental conditions. The period of wetting is usually believed to be more important than the total amount of water falling on a wood surface to increase the MC.

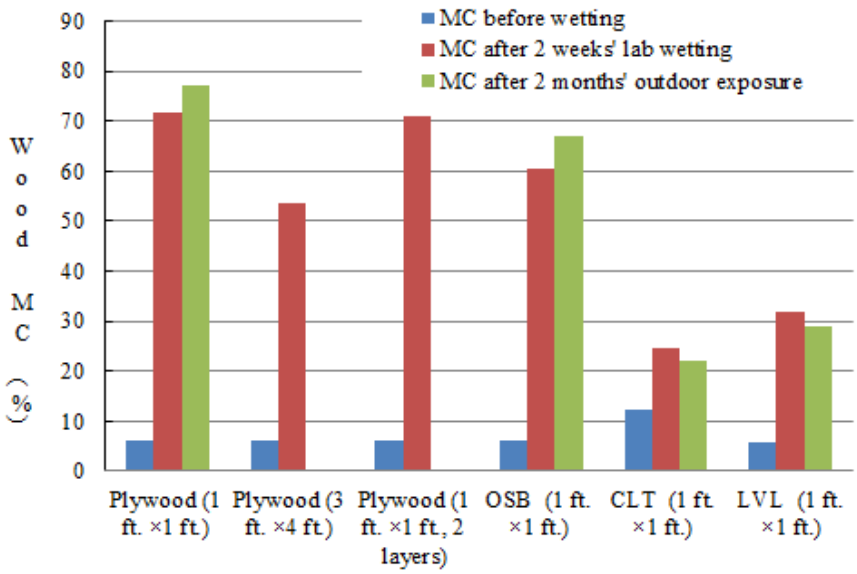

Figure 6: Average moisture content before and after laboratory wetting and after 2 months' outdoor exposure from January to March in Vancouver

The wetting potential of a material may dictate the level of on-site protection needed. The wetting tests showed that these different materials had very different levels of water absorption, or conversely, different levels of resistance to water absorption and internal distribution, when exposed to liquid water sources. These material properties are affected by internal factors such as wood species, manufacturing methods, sizes (e.g., panel thickness), adhesive contents of composite materials, and surface treatment, if present. Most Canadian softwood species, such as S-P-F, Douglas-fir, and hemlock, are known to have high resistance to water absorption and penetration. This was reflected by the low wetting potential of the CLT specimens. Compared to solid wood products, the micro-voids and increased exposure of wood end grains introduced during manufacturing are the main reasons why most composites have higher wetting potentials. However, these same features may facilitate drying under favourable conditions. In general the easier it is for moisture to get in; the easier it would be for moisture to evaporate from a material. However, as further discussed below, drying takes time and reducing wetting is therefore always a higher priority than taking measures to dry wetted wood in terms of moisture management.

Effects of Membrane, Insulation, and Space Heating

Figure 7 shows the large impacts of low vapour permeance materials on the drying rates. When a roof deck, regardless of whether it was plywood, OSB, CLT, or LVL, covered with an impermeable membrane on the top and closed-cell foam underneath, the MC of the wood barely changed during the entire test period of over 6 months. Moisture could not evaporate from the top surface because it was stopped by the impermeable membrane, and could not readily escape from the bottom surface, either, if it was able to

transmit across the thickness of the panel, due to low vapour permeance of the closed-cell spray foam. Inspection following this drying test found dampness in the wood surfaces, even liquid water on the impermeable membrane in some assemblies, and mould growth on several specimens. This confirms that wood should never be closed in with materials with low vapour permeance since they eliminate the drying ability.

When the top surface of a deck specimen was covered with the same impermeable membrane but the bottom surface was not covered with closed-cell spray foam, the drying performance significantly improved for plywood, followed by OSB, and then the LVL specimens. However, the MC stayed flat for the CLT specimens, with and without closed-cell foam underneath the decks. Thick wood panels, such as CLT, do not allow quick moisture transmission across the thickness (McClung et al., 2014). Therefore for thick roof / floor decks in a building, drying towards the interior is expected to be very slow even under favourable conditions and should not be relied on as a practical solution to drying construction moisture or rain leaks in service. More robust design measures, such as integrating an interior ventilation cavity as used in the Wood Innovation and Design Centre should be provided (Finch 2016; Wang et al., 2016).

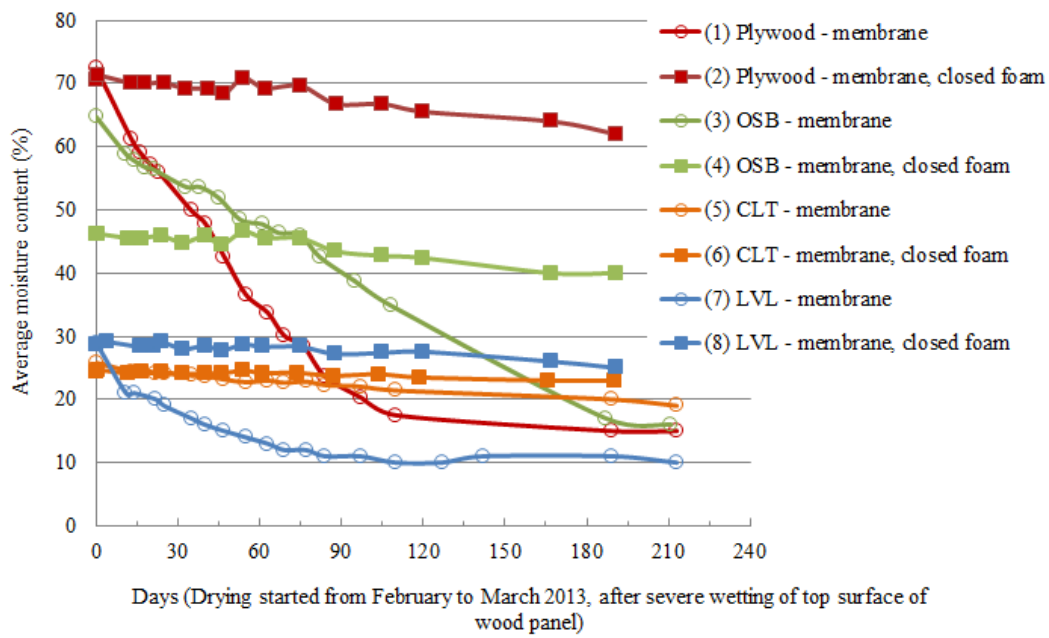

Figure 7: Average moisture content of four types of decks, covered with an impermeable membrane on the top, with and without closed-cell foam underneath during drying in shed

Regarding different roofing materials, it is perceived by some practitioners that compared with impermeable synthetic roofing membranes, standard roofing felt and asphalt shingles should have better "breathability" and therefore would allow wood to dry out. However, this perception did not appear to be borne out by this test. Comparing the two curves in Figure 8 for plywood, with the initially wetted top surface covered with an impermeable membrane or felt + shingles, with and without closed-cell spray foam underneath, the use of felt + shingles showed slightly higher drying rates, but the advantage appeared to be only marginal. Figure 8 also shows that the assemblies built with 2 layers of plywood were much slower in drying, compared with the single layer counterparts, when both were covered with an impermeable membrane on the top.

This test suggested that drying would take a long time once wood panels get severely wet. Figure 8 shows that it took about 30 days for the most permeable assembly in this test, i.e., the plywood covered only with open-cell foam underneath, to dry from 70%, the initial MC after wetting, to 30%. It took 50 days for the plywood covered with felt + shingles on the wetted surface, and 70 days for the plywood covered with impermeable membrane on the wetted surface, to reach a MC below 30%. For the assemblies built with 2-layer plywood, the MC stayed above 40% for about 100 days, and above 30% for about 160 days. Research has shown that at a temperature of about 20°C, decay fungi can colonise kiln-dried wood products when the MC rises to a threshold of 26%, which can be considered the low end of fibre saturation point (typically 26% to 30%) (Wang et al., 2010). Under such marginal moisture conditions, it takes several months or longer for structural damage to occur when all other conditions are favourable for decay; higher MC can speed up decay dramatically (e.g., in weeks). Apparently the risk for the most impermeable assemblies, i.e., with both impermeable membrane and closed-cell foam, would be the highest from the perspective of the wood moisture conditions conducive to decay.

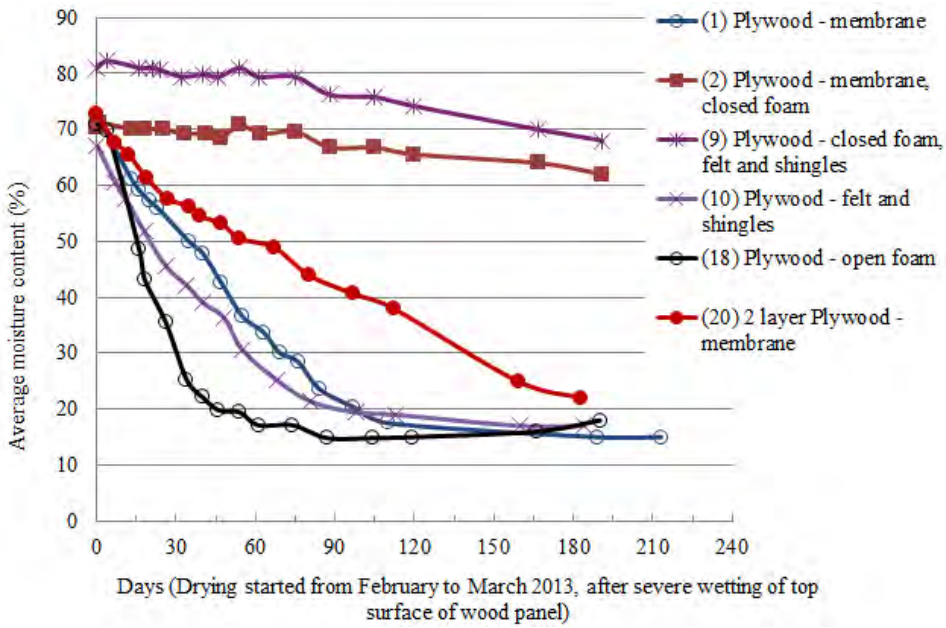

Figure 8: Average moisture content of plywood decks in various roof assemblies during drying in shed

Figure 9 shows the effect of reversed temperature gradients on the drying performance of plywood covered with an impermeable membrane on the top. Forced drying methods, typically space heating can be used to accelerate drying during construction in a relatively convenient and cost-effective way, when necessary. It appeared that space heating provided in the plywood box below dried this large plywood reference specimen relatively quickly. The surface measuring spots in the top layer of plywood right below the membrane, i.e., a location with the highest moisture risk reached a MC of about 20% after about 40 days in a heating season (April, May). Apparently moisture was able to dissipate from underneath, in the direction opposite to the temperature gradients. Increasing temperature in the wet wood increased the internal vapour pressure and the increased vapour pressure gradients must have driven the moisture towards the heated box below. This drying ability under reversed temperature differentials may not be anticipated by all practitioners. The test overall demonstrated the effectiveness of space heating in drying light wood-frame construction before closing-in in a wet climate. However, heating will not be highly effective for drying mass timber construction, as shown below for NLT assemblies.

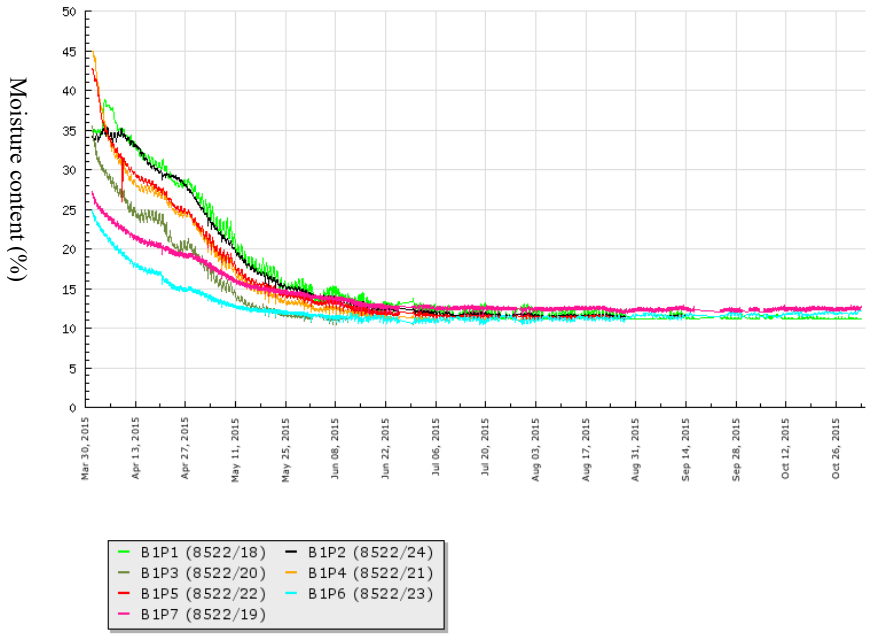

Figure 9: Moisture content readings from sensors installed in different layers of plywood covered with an impermeable membrane on the top and with space heating provided below

(B1, specimen number; P—plywood; number after "P": 1, 2—top layer; 3, 4, 5—middle layer; 6, 7—bottom layer of plywood)

Nail-Laminated Timber

Laboratory Assessment

Built-up assemblies, such as NLT, have been increasingly used, particularly in commercial and industrial construction. They offer many advantages, particularly where large spans are required, compared to traditional light-frame systems built with dimensional lumber and sheathing panels. However, built-up assemblies (including the 2-ply plywood roof assembly tested above) tend to have high wetting but low drying potential, primarily due to the small gaps introduced by mechanical lamination. In typical Canadian practice, the nail lamination of boards is pre-fabricated in a factory, with the sheathing on the top, typically plywood, pre-installed in the factory or installed at the site. The areas where plywood connects the adjacent NLT modules can only be installed at the site to meet structural requirements. Prefabricators also try to pre-install a protective membrane to reduce the risk of wetting during construction (StructureCraft, 2015; Binational Softwood Lumber Council, 2017). This test aimed to assess the wetting and drying performance of a range of NLT assemblies in order to identify practical solutions to on-site moisture management in the North American context (Wang, 2016c).

NLT (called "a beam" when there was no plywood sheathing on the top) was built to simulate a floor or roof deck. Each beam consisted of 6 boards of nominal 2 in. × 8 in. (38 mm × 180 mm) Douglas-fir dimensional lumber, being 900 mm long. In addition to reference beams without any covering material, a few NLT beams were covered with plywood sheathing, with or without a gap in the middle to simulate a joint between plywood sheets in field. In a few test specimens, a type of membrane was installed above the sheathing or between the beam and the sheathing as a potential protection mechanism for the NLT below.

Three types of membranes including Grade D asphalt-impregnated building paper, a vapour-permeable synthetic membrane, and a vapour-impermeable self-adhesive membrane were assessed for their potential protection function against water penetration.

Figure 10: Left: Nail-laminated timber test assemblies under outdoor exposure at FPInnovations' Vancouver laboratory; Right: Nail-laminated timber assemblies undergoing drying above plywood boxes in the shed

In further detail, three groups of assemblies were tested under different wetting and drying conditions. One group consisted of test assemblies, which were pre-built (with a NLT beam only, or together with plywood sheathing and building paper on the top) and subjected to laboratory wetting through spray of water for approximately 18 days, with each spray lasting 5 seconds. It was estimated that about 80 litres of water in total was sprayed on each specimen, roughly equivalent to a rainfall of about 350 mm. The specimens were subsequently set up in the shed for assessing the level of moisture protection that had been provided by the sheathing or the building paper during the wetting procedure and the drying rates afterwards. The second group was subjected to the same scheme of laboratory wetting; but the NLT beam and the plywood sheathing of each assembly were separately wetted by spray of water to simulate the worst scenario of wetting that could occur at a site. They were then assembled into test specimens and installed above the plywood boxes located in the shed for assessing drying performance, with or without an impermeable membrane covering the wetted top surface, and with or without purposely created temperature differentials simulating space heating. In addition, a group of specimens were installed outdoors for assessing their wetting and drying behaviour, including the potential protection provided by each type of membrane products (Figure 10). In each assembly several moisture sensors were installed at various locations to measure the changes in local MC.

Results and Discussion

Moisture Protection Provided by Sheathing or Building Paper during Laboratory Wetting

Overall the wetting scheme used in the laboratory through controlled spray of water was more intense than the natural wetting occurred during the outdoor exposure. For an unprotected NLT beam, the sensors installed in the surface of NLT showed MC of over 40%, indicating that these locations were very wet with MC beyond the upper measurement limit, when the drying test started in the shed (Figure 11). But the surface locations dried relatively quickly under sheltered conditions in the shed, with the MC reaching 20% after about 2 months. However, the central measurement locations showed MC close to 30% at the

beginning; moreover, the MC stayed high for a long period of time. They slowly dropped to 20% at the end of August, 5 months into the drying test after a drier than normal summer. This might have led to decay but the assembly was not opened for inspection.

When there was plywood sheathing on the top (Figure 12), the NLT beam stayed relatively dry. Not surprisingly the plywood showed very high MC, exceeding the upper limit of 45% of the MC measurement system after the laboratory wetting procedure. But it also dried relatively quickly, with the MC falling below 20% in mid-June, after about 2.5 months in the shed. However, when there was a gap in the sheathing, not only the plywood itself but also the NLT beam below showed considerable wetness (Figure 13). This implies that all joints in sheathing should be immediately sealed after installation in field to avoid trapping moisture in the NLT below. When building paper was used for protection, either being installed between the sheathing and the NLT or directly above the sheathing, some moisture was able to pass the sheathing and reach the NLT below (Figure 14). The NLT appeared to be slightly damp with a surface (below plywood) MC of around 20%. This test demonstrated the risk of moisture entrapment in NLT when exposed to rain and a moderate level of protection that may be provided by sheathing or building paper installed above NLT.

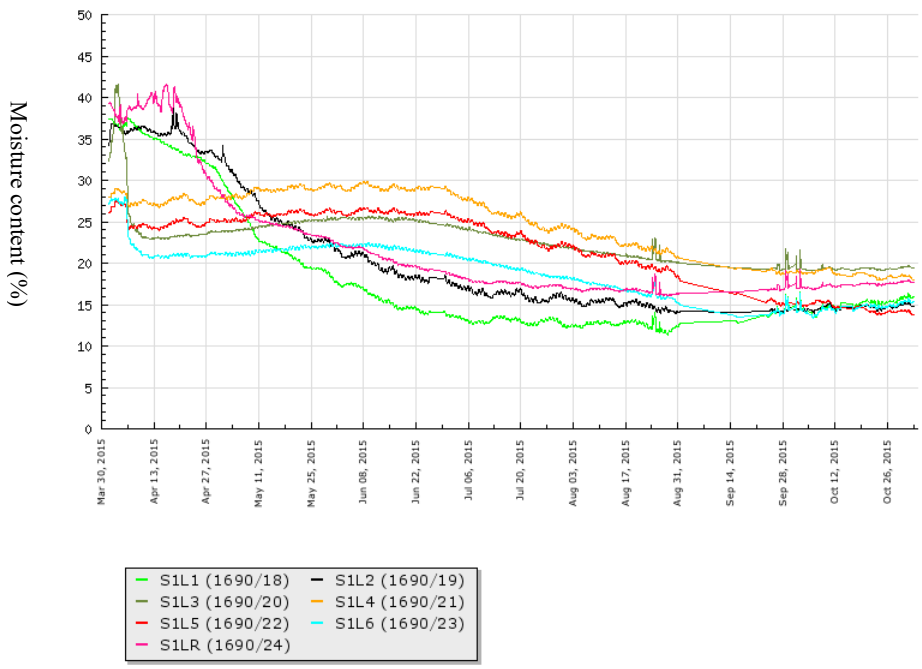

Figure 11: Moisture content in nail-laminated timber without covering sheathing, when drying in a shed after laboratory wetting

(S1—specimen number; L—boards of NLT; number after "L": 1, 2—top surface; 3, 4, 5, 6—central; R—bottom)

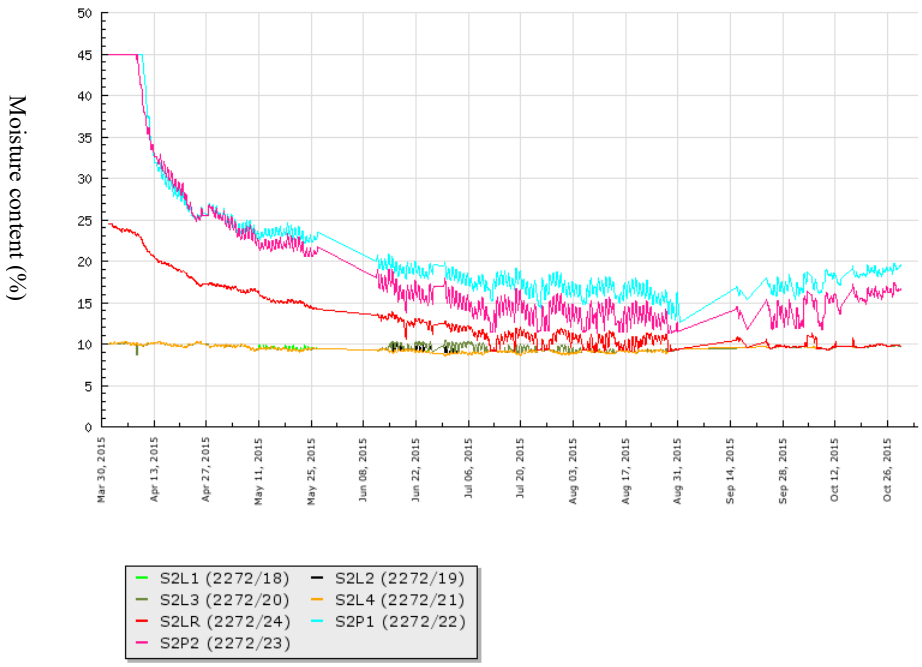

Figure 12: Moisture content readings from sensors installed in S2 beam and plywood sheathing, when drying in a shed after laboratory wetting

(S2—specimen number; L—boards of NLT; number after "L": 1, 2—top surface; 3, 4—central; R—bottom; P—plywood; P1, P2—middle layer of plywood)

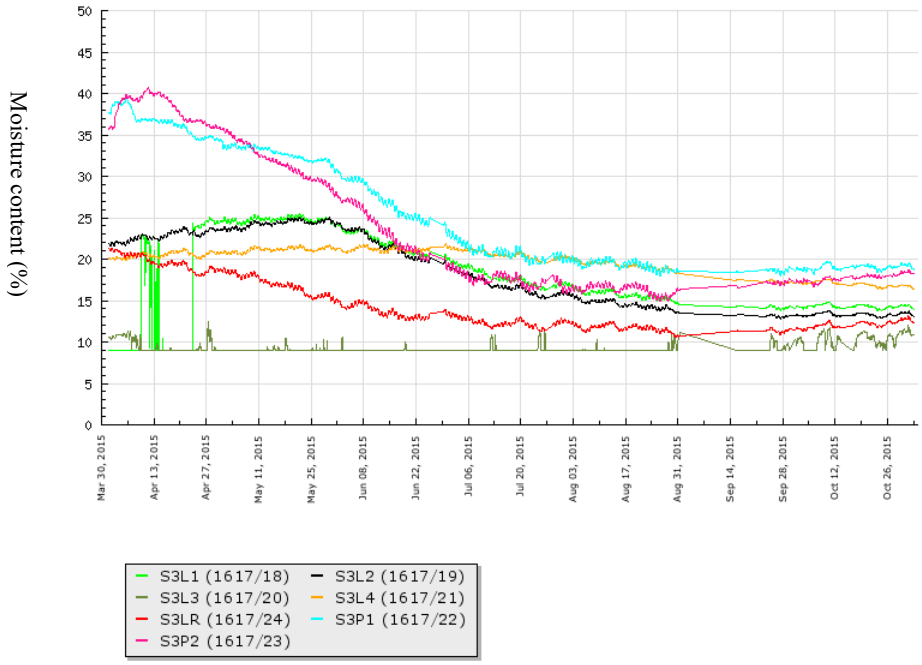

Figure 13: Moisture content in nail-laminated timber with covering plywood sheathing, without gap in the sheathing, when drying in a shed after laboratory wetting

(S3—specimen number; L—boards of NLT; number after "L": 1, 2—top surface; 3, 4—central; R—bottom; P—plywood; P1, P2—middle layer of plywood)

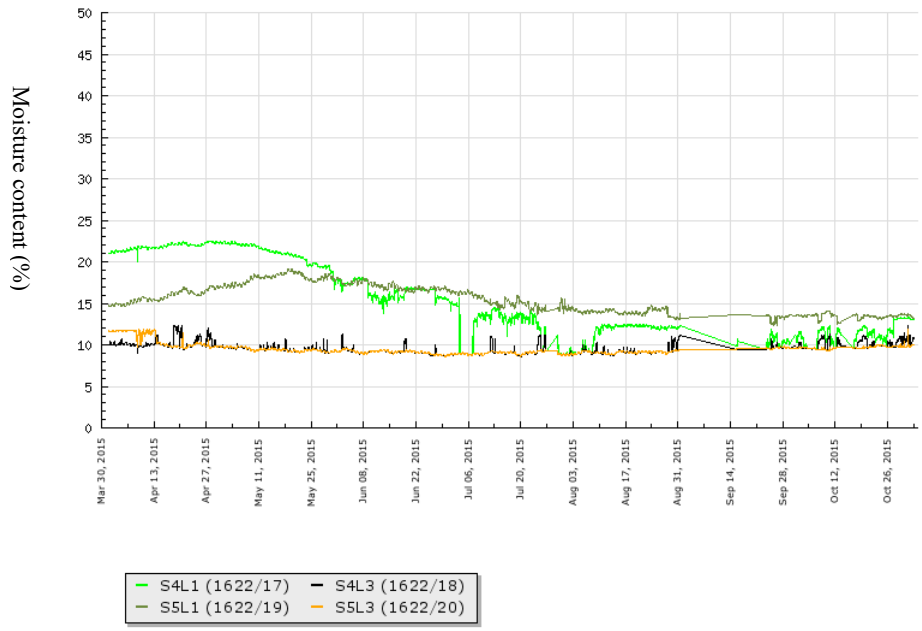

Figure 14: Moisture content in nail-laminated timber with building paper installed for protection during laboratory wetting, when drying in a shed

(S4/S5— specimen number; L—boards of NLT; number after "L": 1—top surface; 3—central)

Effect of Space Heating on Drying

When a wetted test assembly which included both NLT beam and plywood without any covering membrane was installed above a plywood box without heating provided below, both plywood and NLT beam dried slowly in the shed (Figure 15). Most measurement spots in the NLT beam stayed above a MC of 20% during the entire test of 7 months, except for the bottom surface, where the MC reduced below 20% in about 2 months. The plywood also stayed wet, with the MC above 20% throughout the entire test period. When the same assembly was set on a plywood box with heating provided inside, the drying of both plywood and NLT beam appeared to slightly speed up, with the MC in plywood reduced to around 20% after about 2 months. But the central areas of NLT did not reach 20% until the end of August, after about 5 months into the drying test.

The worst scenario occurred when the assembly was covered with a vapour-impermeable membrane and no heating was provided in the plywood box underneath. The MC readings from most measuring locations in both of the plywood and the NLT beam stayed flat throughout the entire drying test after the laboratory wetting procedure. Providing heat appeared to slightly speed up drying of the portion of the NLT beam right above the heated space; the heating did not improve drying of the plywood sheathing on the top (Figure 16). The MC readings from the top and the middle layer of the plywood increased in the summer likely due to moisture redistribution resulting from the outward vapour gradient; however, moisture dissipation to the exterior was completely stopped by the impermeable membrane installed on the top.

The test indicates that when materials are wet, they should be dried prior to assembly or enclosure. An assembled system will have greatly reduced drying ability, even when there is no impermeable material

(e.g., vapour-impermeable membrane, plastic foam) to stop moisture evaporation, and even under forced drying conditions. The water and vapour permeability of a material has a large effect on the drying ability. Most wood products are not permeable enough to allow quick dissipation of moisture; the internal resistance to moisture movement also greatly increases with increase in dimensions. Space heating is effective in accelerating drying of thin or small elements (e.g., plywood). But its effectiveness greatly diminishes with increase in the depth of products / assemblies, since wood is a good insulator with poor heat conduction inside. For NLT, some level of air flow between boards may improve heat transfer and consequently the drying rates. But the boards are closely laminated and fastened to meet structural requirements; moreover, any gap between boards further reduces in wet assemblies resulting from wood swelling. However, when NLT becomes wet during construction, heating plus ventilation, such as in a means of blowing hot air, remains probably the most practical solution to accelerating drying, especially in a cold and damp climate. Ideally the hot air should be directly blown to the NLT surface, i.e., removing any sheathing or membrane on the top, when present in order to accelerate evaporation from the surface. Impermeable membranes, when present should always be removed prior to use of forced drying since they inhibit drying.

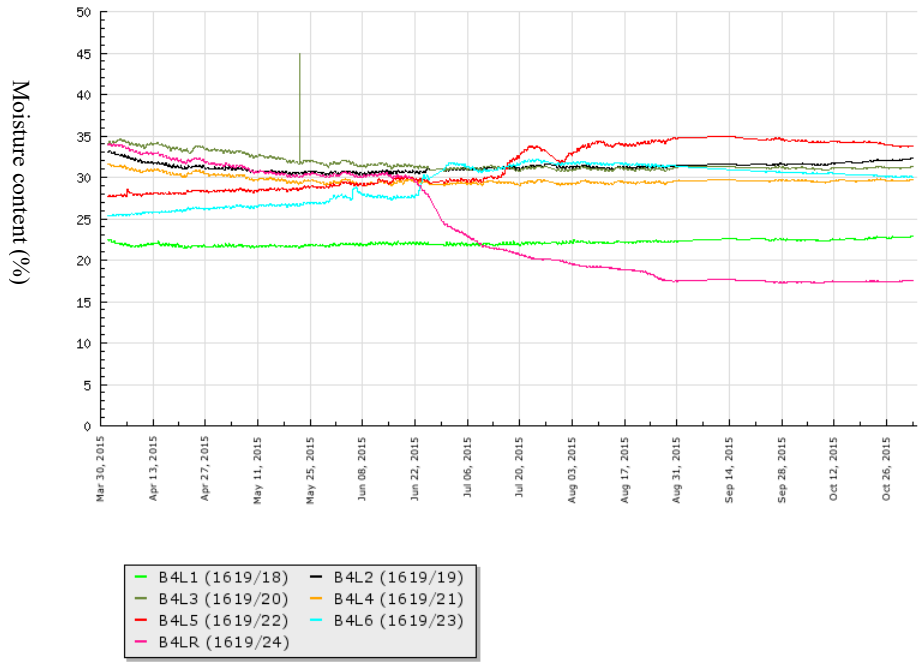

Figure 15: Moisture content readings from sensors installed in nail-laminated timber, covered with plywood sheathing, without membrane on the top or space heating below

(B4—specimen number; L—boards of NLT; number after "L": 1, 2—top surface; 3, 4, 5, 6—central; R—bottom)

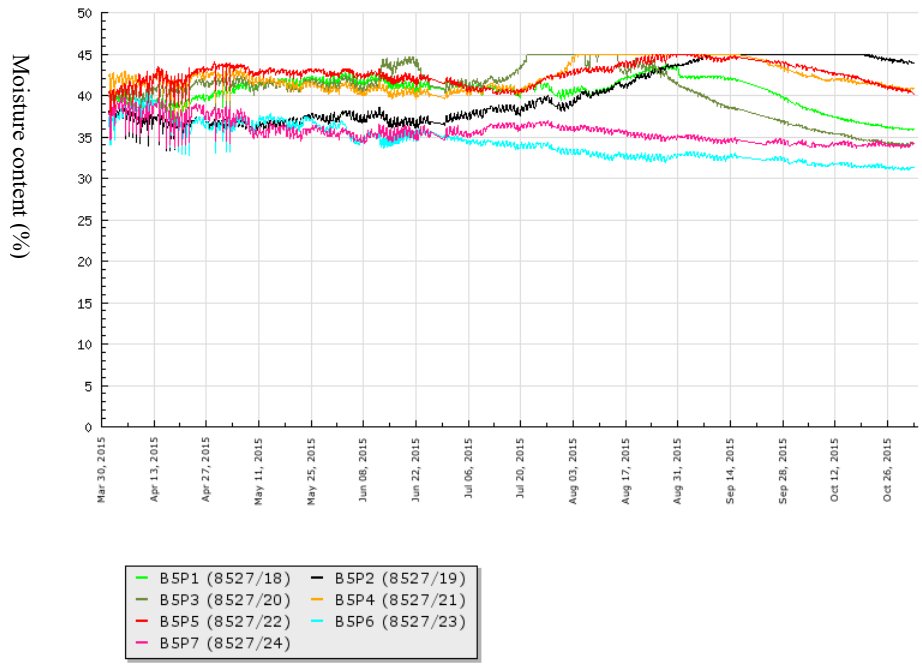

Figure 16: Moisture content readings from sensors installed in plywood sheathing covering nail-laminated timber, with membrane on the top and space heating below the NLT

(B5—specimen number; P—plywood; number after "P": 1, 2—top layer; 3, 4, 5—middle layer; 6, 7—bottom layer of plywood)

Protection Provided by Membrane during Natural Exposure

During the outdoor exposure the reference NLT specimen (without plywood or membrane on the top) showed high MC, not only in the top surface but also in the central areas, due to intense rain after the test was set up in December. Regarding moisture protection provided by a membrane product, it appeared that the impermeable membrane provided the best protection to the plywood and NLT below. By comparison, neither the building paper nor the vapour-permeable synthetic membrane was able to completely stop moisture penetration, even when there was no small hole caused by staples as in field; the MC readings from the top surface of plywood remained around 35% and those from the NLT roughly below 25% throughout the test. The building paper appeared to be slightly more water-resistant than the synthetic membrane tested. Integrating either of them between the beam and the plywood provided slightly better protection to the NLT compared to installing it above the sheathing. Note that installing a synthetic membrane on a horizontal structure, such as a floor or a roof, may make the surface slippery and become a safety hazard for construction.

In terms of implications on practical on-site protection measures, heavy-duty roofing membranes are much more water-resistant and can provide better protection than the commonly used vapour-permeable membranes used for exterior walls. Pre-installing a roofing membrane on a sheathed NLT can work well for a roof structure, when the protection work is coordinated with the roofer and other parties involved. Note that the roof areas that are to be connected with adjacent NLT or plywood sheathing and cannot be pre-assembled due to structural reasons should be kept to a minimum. Those areas will require immediate protection once assembled at the site to prevent moisture ingress and entrapment from the joints.

However, for other NLT applications such as floors and elevator shafts, where installing a roofing membrane or other impermeable membrane becomes not practical, a light-duty membrane may be pre-installed as a temporary protection measure. Note some moisture may pass through the membrane, particularly when used on a horizontal surface. The assemblies should therefore be sheltered by other parts of the building (e.g., roof) for more reliable protection as soon as the construction allows. Space heating may become necessary to speed up drying if rainwater is found to have penetrated the protective membrane during construction. If the selected membrane is vapour-permeable, the membrane may be installed right above a NLT deck if the sheathing has to be installed at the site. This will provide slightly better protection to the NLT and the sheathing installed at the site also avoids potential damage to the membrane from wear and tear during construction. It should be pointed out that compared to relying on a protective membrane, the most effective and reliable on-site protection can be provided by a temporary roof / shelter (Wang, 2016a). In a wet climate, planning the work around a temporary roof may become cost-effective as it brings certainty to protecting products / assemblies that are highly susceptible to entrapping moisture and tend to dry slowly after wetting incidents.

WETTING AND DRYING OF CLT FLOORS IN BROCK COMMONS BUILDING

Field Measurement

Exposure of small panels can be useful for assessing moisture uptake, but there is no substitute for field performance data. The moisture levels in the 18-storey Brock Commons building on the campus of the University of British Columbia were assessed during the construction (Wang and Thomas, 2016). The building is 53 m high with 17 stories of mass timber construction sitting on a concrete podium. The five ply (169 mm thick) CLT floors were point supported by multiple columns, mostly composed of glue-laminated timber, but with parallel strand lumber (PSL) columns on the lower floors. Related to this work, there was another monitoring study of wood MC and building movement in this building (Mustapha et al., 2017).

Erection of mass timbers started in early June and was completed in mid-August 2016. An average of two floors was erected every week by nine workers. Comprehensive on-site moisture protection measures were applied, ranging from reducing exposure time to rain through a high level of prefabrication, good construction sequencing and quick installation, immediately sealing joints upon installation of CLT floors, to applying water repellent on CLT floors (Wang and Thomas, 2016). Wood MC was measured on periodic site visits (roughly every two weeks), covering both dry weather and conditions after rain events. For example, MC readings were taken on newly installed floors and then 1, 4 and 14 days after heavy rain to assess the impact of exposure to rain. There were a total of 31 rainy days and 124 mm of precipitation over the period of 71 days for timber installation. When it was not raining, the weather was overall warm and windy, creating favorable conditions for drying wood.

The MC measurements focused on CLT floor panels using a hand-held Delmhorst RDM3 resistance-based moisture meter. The measurements covered “normal” wood (i.e., no visible defect, away from end grain), end grain close to finger-joints, and blue-stained sapwood of beetle-killed lodgepole pine. About 20 readings were taken 5 mm inward from the surface at random locations on CLT panels located in the southeastern part of each floor. Deeper measurements were not conducted because of concern about

potential damage to the floor. No measurement was made once a floor was covered with concrete topping.

Results and Discussion

The measurements showed that the MC readings from the CLT panels during the entire period of installation did not change greatly (Figure 17). The average MC ranged from 12% to 18%, with a standard deviation within 2.5%. It was found that the rain events, including the heavy showers on June 23 with a daily precipitation of 13 mm, did not have a large impact on MC of the CLT panels on the 5th floor, which was directly exposed to rain after installation (Figure 18). This was again confirmed later on the top floor (Level 18), after the mass timbers were installed and a few rain events occurred before the roof was installed. Overall the wetting was not severe enough for us to evaluate drying performance of CLT. However, dripping of water through joints of CLT panels and gaps within panels, despite taping at joints, was found to cause wetting to the underneath ceiling and columns, PSL columns in particular. The risk of moisture will likely increase under wetter and less favourable weather conditions for drying (e.g., in the winter in this climate), which may require more effective protection methods.

It was noticed that the MC readings were higher, typically by a few percentage points, when measured on CLT panels with water present after rain. End grain generally showed higher readings after rain events. Measurement at end grain of CLT panels was not emphasized in this study since end grain typically gets wet easily but also dries out quickly, when conditions allow. Blue-stained wood was confirmed to retain a higher amount of moisture than non-blue-stained wood. Minimizing the time of exposure to rain remains the most critical to reduce built-in moisture and its potential consequences in such mass timber construction.

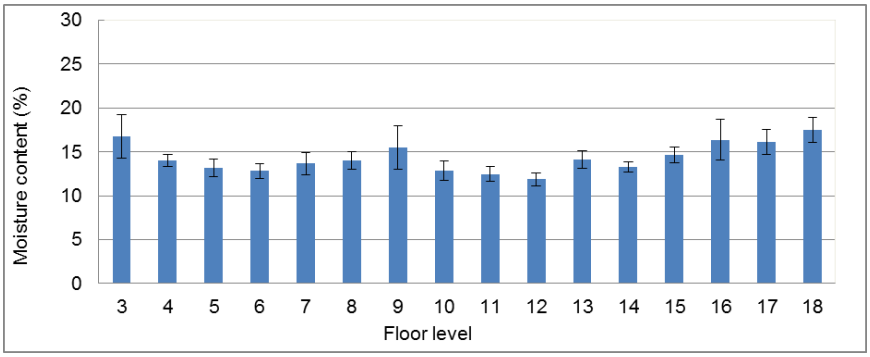

Figure 17: Moisture levels in CLT panels on different floors during the construction of the 18-storey Brock Commons building

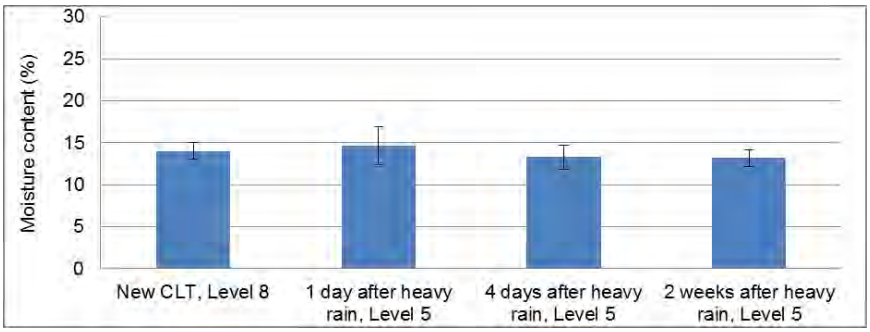

Figure 18: Moisture levels in CLT immediately after installation, and 1, 4 and 14 days after heavy rain on level 5 in the 18-storey Brock Commons building

CONCLUSIONS

The major conclusions and implications that can be drawn from these studies include:

- Without purposely provided on-site protection, the MC of "S-Dry" S-P-F and Douglas-fir dimensional lumber remains around 20% on average before a light wood-frame building is sheltered and heated in the wet season in the coastal climate of British Columbia. The MC level is considerably lower, around 15%, during framing in relatively dry weather. As expected on-site moisture protection remains important in a wet season.

- Different wood materials have different wetting and drying potentials and may require different levels of on-site moisture protection. In general thin composite panels including plywood and OSB have high water absorption, when exposed to water; but may also dry relatively quickly under favourable weather conditions. CLT, a type of glue-laminated solid wood panel, shows a relatively low wetting potential, especially in the central areas of boards. However, those areas also dry very slowly once wetted. As an example of built-up assemblies, NLT floor panels have a high potential to trap moisture between boards; the subsequent drying can be very slow. Assemblies that have poor drying performance after wetting require more attention to reducing the wetting potential through on-site protection and also to increasing the drying capacity through robust design measures.

- Wet wood members should always be dried prior to further assembly or enclosure. Drying is much slower in thicker or built-up members / assemblies, such as 2-layer plywood, LVL, CLT, and NLT. Any roof / floor deck should be avoided to be enclosed in materials with low vapour permeance (e.g., impermeable membrane on the top and closed-cell spray foam underneath) to avoid eliminating the drying ability.

- For NLT, a small degree of protection can be provided by the sheathing on the top, such as plywood when it is installed prior to exposure. The gaps in the sheathing, when pre-installed, should be immediately sealed upon installation to prevent trapping moisture in the NLT. However, the sheathing, typically being absorptive of water, should also be pre-protected, if possible.

- On-site moisture protection may be provided by a membrane product. The protection provided by the building paper appeared to be slightly better than that by the vapour-permeable synthetic membrane assessed in this test; but neither of them showed adequate protection during the outdoor exposure. In field these products are only recommended for use as a temporary protection measure when more advanced methods are not possible. The building paper or synthetic membrane may be pre-installed above a NLT in a factory if the structural sheathing has to be installed at the site. Note a synthetic membrane may make a horizontal surface slippery and cause a safety hazard in construction.

- Space heating is most effective in drying relatively thin products / assemblies, such as plywood, even under reversed temperature differential conditions (, when the panel is covered with an impermeable membrane on the top with no insulation underneath) . However, heating is much less effective in drying thick and large built-up members, such as NLT, particularly when it is covered by an impermeable membrane.

- Field measurements during the 18-storey Brock Commons project confirmed that CLT panels made with Canadian S-P-F wet up slowly. On-site protection should be focused on measures to reducing the time of exposure to rain and also protection of interior finishing and fire protective measures (e.g., gypsum) below.

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