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TESTING R22+ MASS TIMBER WALLS FOR HYGROTHERMAL PERFORMANCE IN THE VANCOUVER CLIMATE: CONSTRUCTION AND INSTRUMENTATION

PROJECT NUMBER: 301014059

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March 2021

Project number: 301014059
Technical Report 2021 N45

ACKNOWLEDGEMENTS

The project is primarily funded by Natural Resources Canada (Canadian Forest Service) through the Technology Transfer Program under the contribution agreement existing between Natural Resources Canada and FPInnovations.

Input was received from RDH Building Science Inc., Morrison Hershfield, Nordic Structures, ROCKWOOL™, and Soprema regarding the test plan of this study. Nordic Structures, ROCKWOOL™, and Soprema contributed materials.

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EXECUTIVE SUMMARY

Mass timber construction is expected to be permitted by the 2020 National Building Code of Canada for buildings up to 12 storeys. This new study aims to generate hygrothermal (i.e., moisture, thermal) performance data for highly insulated cross-laminated timber (CLT) walls meeting the R22 effective (RSI 3.85) requirement for buildings up to six storeys in the City of Vancouver. The overarching goal is to identify and develop durable exterior mass timber walls to assist in the design and construction of low-carbon, energy efficient buildings across the country. Eight CLT wall panels, each measuring 1200 mm (4 ft.) wide and 2400 mm (8 ft.) tall, in four different configurations and two orientations (north, south), are tested as the exterior walls of a test hut located in the rear yard of the FPInnovations laboratory in Vancouver. A light-wood-frame reference wall is included in both orientations to compare the hygrothermal performance including thermal mass effect. One replicate of the test walls (No. 1-No. 5) faces north (i.e., wall panels N1-N5) and the other (i.e., wall panels S1-S5) faces south. This report, first in a series on this study, documents the initial construction and instrumentation.

Installation and finishing of these wall panels took place from August 2020 to January 2021. The CLT panels, provided by a Canadian manufacturer, were made with Spruce-Pine-Fir. The five types of wall assemblies consist of different insulation strategies and materials. Walls No. 1 and No. 2 were built with 3-ply CLT (89 mm (nominal 4 in.) in thickness), together with an interior service wall framed with 38 mm by 90 mm (nominal 2 in. by 4 in.) dimension lumber with its 90-mm deep stud cavities filled with nominal R14 stone wool batt insulation. Wall No. 1 had exterior insulation of 38-mm (1.5 in.) thick rigid stone wool and No. 2 had 25-mm (1 in.) thick foil faced-polyisocyanurate (polyiso) board. Walls No. 4 and No. 5 were built with 5-ply CLT (143 mm (nominal 6 in.) in thickness), with a 19-mm deep interior cavity framed with 19 mm by 38 mm (nominal 1 in. by 2 in.) furring to accommodate sensors. Wall No. 4 had 50-mm (2 in.) thick polyiso and No. 5 had 75-mm (3 in.) thick rigid stone wool exterior insulation. Wall No. 3, a split-insulated light-wood-frame wall, was built with 38 mm by 140 mm (nominal 2 in. by 6 in.) dimension lumber, with its wall stud cavities filled with glass fibre batt insulation (R19 compressed from nominal R20) and exterior-insulated with 38-mm (1.5 in.) thick rigid stone wool board. All 10 wall panels had the same self-adhesive, vapour-permeable membrane as an exterior moisture barrier (or called weather barrier, water-resistive barrier). In terms of interior vapour diffusion control, given the expected low permeance of the CLT, none of the CLT walls had any special control measure; while wall No. 3 had sheet polyethylene (0.15 mm (6 mil) thick), a traditional interior vapour barrier in Canadian climates installed between the wall studs and the drywall. Efforts (e.g., installing two-layer interior gypsum board) were made for the CLT walls to meet the encapsulated mass timber construction requirements proposed for the 2020 National Building Code of Canada. The effect of air leakage on moisture performance is not dealt with in this study, as all wall panels were built and installed to be airtight.

This study focuses on measuring the wood moisture content (MC), temperature, and relative humidity (RH) (and the corresponding vapour pressure gradients) through each wall assembly to assess its hygrothermal performance. Controlled moisture loads, in the form of vapour (achieved by maintaining a relatively high indoor RH) and liquid water (achieved by periodically injecting water to the wetting pads installed on the wood panels) are employed to stress these

walls for investigating their moisture-related behaviour. After the wall panels and most instruments were installed but with the CLT directly exposed to the interior environment, a high indoor RH in range of 70-80% was maintained, starting mid-December 2020 inside the test hut to condition the wood to achieve comparable moisture gradients among the eight CLT panels. The test walls were closed in with interior framing (and interior insulation of walls No. 1 and No. 2) and drywall installed, followed with interior finishing in late January 2021. The indoor RH was afterwards set to be around 50%. Water injection is planned to start in the summer of 2021. Test results and performance of these walls will be presented and discussed in future reports.

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1 OBJECTIVES

This project is one of the efforts to assist Canadian jurisdictions, such as the province of British Columbia in implementing low-carbon, energy efficient mass timber buildings.

By testing four R22+ cross-laminated timber (CLT) wall assemblies together with a light-wood-frame reference wall using a test hut in the climate of Vancouver, this project focuses on the following objectives:

- Generate hygrothermal performance (i.e., moisture-related and thermal resistance/mass) data for CLT wall assemblies anticipated to be commonly used to build low-carbon, energy efficient buildings across Canada;
- Assess thermal mass effect of mass timber walls;
- Validate hygrothermal modelling to improve design tools for mass timber construction;
- Develop specific recommendations on durable and energy efficient CLT wall assemblies for practitioners;
- Facilitate use of prefabricated mass timber walls.

2 INTRODUCTION

Mass timber- including cross-laminated timber (CLT)-based exterior walls are gaining interest for both residential and non-residential buildings as gravity-load-bearing; and more commonly, non-gravity-load-bearing exterior walls. Worldwide, the market of non-bearing exterior walls of mid-rise and taller buildings is dominated by glass window/curtain walls and light gauge steel walls mostly due to fire regulations. But these exterior wall systems all face challenges in achieving high building energy efficiency and good indoor thermal comfort due to issues, such as high thermal bridging through metal components and undesirable solar heat gains through large glazing. Mass timber-based alternatives are well positioned to offer improved thermal performance due to minimal thermal bridging, ease of adding extra insulation, and possibly providing benefits of thermal mass (Karacabeyli and Gagnon 2019). Aside from the likely reduced operational energy consumption and carbon emissions, mass timber has inherently sequestered carbon to minimize embodied emissions. The 2020 edition of the National Building Code of Canada is expected to allow mass timber buildings up to 12 storeys, with encapsulated mass timber construction requirements to ensure the highest level of fire safety. Aside from use in new mass timber construction, mass timber walls may also provide a competitive alternative for non-bearing infill walls of non-combustible construction (e.g., concrete) and deep energy retrofits of the building envelopes of mid-rise and taller buildings. In terms of implementation, industrialized construction is the most suitable for mass timber systems to improve construction quality and efficiency and also to achieve the tight tolerances required for taller and larger buildings.

Related to Canadian energy regulations of large buildings, an energy model code, the National Energy Code of Canada for Buildings (NECB), was first published in 2011 (NRC 2011) and has been adopted, with its different editions, by the provinces of British Columbia (BC), Ontario, and

Alberta. Provinces including BC and Ontario also reference the ASHRAE Standard 90.1 (ASHRAE 2010) for meeting the energy requirements of large buildings. In BC, the Energy Step Code was enacted in April 2017 for both Part 9 and Part 3 buildings to transition towards net-zero energy ready by 2032 (Government of British Columbia 2017). Aside from these building codes and standards, wood is often the choice of material when a building design follows a more stringent energy program, such as Passive House (Passivhaus).

Given the overall "envelope first" approach adopted by the newer energy codes and programs, the building envelope must be built to be highly airtight and thermally efficient to meet the new energy requirements. For example, the City of Vancouver requires RSI 3.85 (R22 effective) for above-grade walls of residential construction up to six storeys (BC Housing 2017; City of Vancouver 2018). While measures to increase the thermal resistance and the impact of adding insulation on hygrothermal performance of light-wood-frame building envelope systems are generally known since quite a few studies have been completed across North America in the past two decades (Straube et al. 2002; Armstrong et al. 2009; Smegal et al. 2013; Fox 2014; Gauvin 2014; Trainor 2014; Glass et al. 2015; Tariku and Ge 2015; Tariku et al. 2015; Glass et al. 2016; Wang 2021), the hygrothermal behavior of mass timber systems remains to be further investigated. Up to now only a few small-scale studies have been conducted for Canadian climates and products (Lepage 2010; Alsayegh et al. 2013; McClung et al. 2014). Investigating their moisture-related performance in realistic service environments of building envelopes is urgent since durability has a large impact on a building's service life and maintenance needs and costs, particularly as the new energy codes are implemented. Moreover, the newly published CSA S478 standard on "Durability in Buildings" (CSA 2019), which is expected to be referenced by the 2025 NBCC, requires performance data/prediction in building design, particularly for newer and innovative systems. Focusing on generating hygrothermal performance data of CLT-based exterior walls and improving the related hygrothermal simulation tools, this project aims to accelerate innovations in the building envelope systems of mid-rise and taller buildings. It is anticipated that the test results will help improve recommendations for durable and energy efficient mass timber wall assemblies that practitioners can readily use, instill confidence in the newer mass timber-based envelope systems, and thereby assist in the design and construction of low-carbon, energy efficient buildings across the country. As the first one of this study, this report documents the construction and instrumentation of the test walls at the test hut. The walls' performance and related hygrothermal modelling will be reported and presented in the future.

3 STAFF

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4 MATERIALS AND METHODS

4.1 Study Overview

The project focuses on assessing the hygrothermal performance of four types of thermally efficient CLT wall assemblies, together with one light-wood-frame reference wall, under a controlled interior environment in the Vancouver climate. The test hut is located in the rear yard of the FPInnovations laboratory and positioned to be well exposed to the elements (Figure 1; Figure 2). The frame of its walls was built to provide five openings, each measuring 1200 mm wide (4 ft.) and 2400 mm (8 ft.) tall, separated by structural columns in both the south and the north orientations. The five test walls (No. 1-No. 5) consist of different insulation strategies/materials, each providing a theoretic effective thermal resistance slightly exceeding R23 (RSI 4.05, see Appendix II, Table 2), considering the thermal bridging caused by structural framing. One replicate of the walls was installed north-facing (panels N1-N5), with the other facing south (panels S1-S5) (Figure 2). Installation and finishing of these walls took place from August 2020 to January 2021.

The study focuses on measuring wood moisture content (MC), temperature, and relative humidity (RH) (and the corresponding vapour pressure gradients) through each test wall to assess its hygrothermal performance. Controlled moisture loads, in the form of vapour (achieved by maintaining a relatively high indoor RH of around 50%) and liquid water (achieved by injecting water to the wetting pads pre-installed on the wood panels) are employed to stress the walls for investigating their moisture-related behaviour. A type of heat flux sensor will be used to provide additional data about their thermal performance.

Figure 1. The exterior of finished test hut.

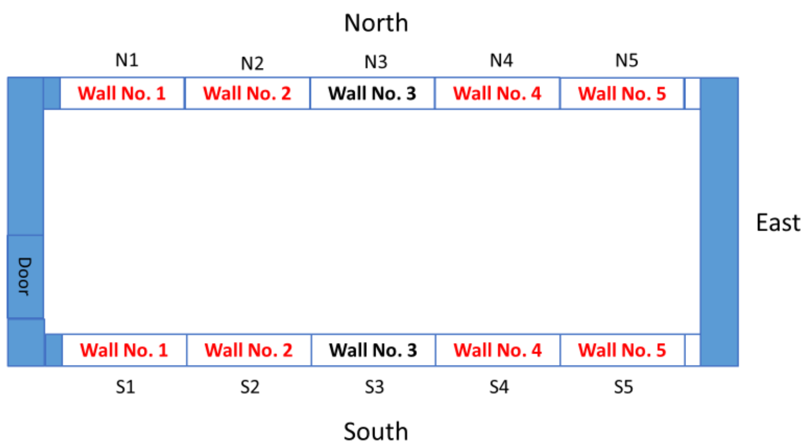


Figure 2. Layout of 10 test wall panels at the test hut.

4.2 Test Matrix

This test focuses on assessing the effects of varying insulation strategies/materials while minimizing the number of variables to better investigate the differences in both moisture-related (i.e., wetting, drying) and thermal (i.e., resistance, mass) behaviour of the test walls under the same environmental conditions. Walls No. 1 and No. 2 were built with 3-ply CLT (89 mm (nominal 4 in.) in thickness), together with an interior service wall framed with 38 mm by 90 mm (nominal 2 in. by 4 in.) dimension lumber, with its 90-mm deep cavities filled with nominal R14 stone wool batt insulation. Such a non-structural interior wall is provided in many highly energy efficient walls, especially solid walls such as CLT to accommodate interior services (e.g., electricity). Wall No. 1 had exterior insulation of 38-mm (1.5 in.) thick rigid stone wool while No. 2 had 25-mm (1 in.) thick impermeable, foil faced-polyisocyanurate[1] (polyiso) exterior insulation. Different from walls No. 1 and No. 2, walls No. 4 and No. 5 were built with 5-ply CLT (143 mm (nominal 6 in.) in thickness), both having an interior cavity framed with 19 mm by 38 mm (nominal 1 in. by 2 in.) wood furring. The 19-mm deep cavity, with the depth kept minimal to avoid complicating fire encapsulation measures[2], was created to accommodate the sensors to be installed from the interior surface. Wall No. 4 had exterior insulation of 50-mm (2 in.) thick foil faced-polyiso and No. 5 had 75-mm (3 in.) thick, rigid stone wool exterior insulation. Wall No. 3, a split-insulated light-wood-frame wall built with 38 mm by 140 mm (nominal 2 in. by 6 in.) dimension lumber, had glass fibre batt insulation (R19 compressed from nominal R20) in its stud cavities and 38-mm (1.5 in.) thick, rigid stone wool exterior insulation. This wall[3] had been tested in the previous study, with 19 months' data collected from three orientations (north, south, and east) (Wang 2021). All these 10 wall panels had the same self-adhesive, vapour-

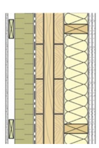
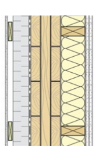
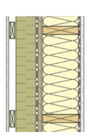
[1] The polyisocyanurate exterior insulation product used is a closed-cell polyisocyanurate foam insulation board laminated with a radiant barrier quality reflective foil facer on the back side and a non-reflective aluminum facer on the top surface, designed to achieve a high R per inch (R6.5/in.).

[2] It was consulted with Christian Dagenais and Lindsay Ranger about the new requirement of encapsulated mass timber construction proposed for the 2020 National Building Code of Canada. It was understood the requirements may be fine-tuned in the final publication.

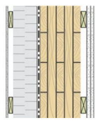
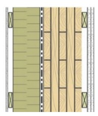
[3] The wall tested in the previous study had a small variation by using a type of loose-sheet, vapour-permeable sheathing membrane, but is expected to perform hygrothermally similarly to the wall No. 3 in this study.

permeable membrane as the exterior moisture barrier (or called weather barrier, water-resistive barrier). A self-adhesive product, instead of a likely more economical loose-sheet membrane was used since one of the objectives of this study was to facilitate off-site production of non-bearing mass timber exterior walls. Self-adhesive membranes typically provide improved strength and robustness and can reduce damage that could occur during transportation and installation of prefabricated components, compared to loose-sheet products. In terms of interior vapour diffusion control, none of the CLT walls had any additional control measure since each CLT panel was expected to have vapour permeance low enough to function as a vapour barrier[4], which is defined by Canadian building codes to have a dry-cup vapour permeance below 60 ng/(Pa•s•m^2) (about 1 US perm) (NRC 2015). By comparison, wall No. 3 had sheet polyethylene (poly, 0.15 mm (6 mil) thick), a traditional interior vapour barrier installed between the wall studs and the drywall, as commonly used in light-wood-frame construction in Canada. Additional efforts were made for the CLT walls to meet the proposed requirement of encapsulated mass timber construction for the 2020 NBCC. These included installing two layers of interior gypsum board and using stone wool batt insulation with proven fire performance for the interior service walls of wall assemblies No. 1 and No. 2, aside from minimizing the interior cavities' depth of walls No. 4 and No. 5. The effect of air leakage on moisture performance is not dealt with in this study, as all wall panels were built and installed to be airtight. The details of the wall assemblies are summarized in Table 1.

Table 1. Summary of test wall assemblies.

Test wall	Interior finish	Interior service cavity	CLT panel (or reference wood-frame)	Exterior insulation	Effective R
No. 1 	Regular latex paint on 2 layers of drywall	Nominal 2 X 4 framing with R14 stone wool batt insulation	CLT, nominal 4 in. (89 mm)	1½" (38 mm) rigid stone wool, R6	23.8
No. 2 				1" (25 mm) faced-polyiso, R6.5	24.2
No. 3 	Poly as a vapour barrier installed between wall studs and 1 layer of drywall; regular latex paint on drywall	--	Nominal 2 X 6 framing with R-20 fiberglass batt	1½" (38 mm) rigid stone wool, R6	23.0

[4] A 4 in. thick CLT panel has vapour permeance of approximately 18 ng/(Pa•s•m^2) (about 0.3 US perm) and a 6 in. CLT panel has vapour permeance of approximately 12 ng/(Pa•s•m^2) (about 0.2 US perm) at about 50% relative humidity, based on preliminary testing (Alsayegh et al. 2013).

Test wall	Interior finish	Interior service cavity	CLT panel (or reference wood-frame)	Exterior insulation	Effective R
No. 4 	Regular latex paint on 2 layers of drywall	Nominal 1 in. (19 mm) furring[5]	CLT, nominal 6 in. (143 mm)	2" (51 mm) faced-polyiso, R13.1	24.3
No. 5 				3" (76 mm) rigid stone wool, R12	23.2

4.3 Preparation and Installation of Test Walls

The CLT panels used in this study were made with Spruce-Pine-Fir (predominantly black spruce), provided by a Canadian manufacturer. The insulation products and the self-adhesive vapour-permeable membrane were also provided by local manufacturers. All other materials were purchased from building supply stores.

A preparation and installation plan was carefully developed in advance to optimize the procedures and the sequencing, partially for a purpose of minimizing the needs of lifting and moving the CLT panels since they were heavy. Each CLT panel was pre-treated in the laboratory, starting in early June 2020, before site installation. From the interior surface of each panel, two sets of holes (five holes/set including four holes for installing two pairs of moisture pins and one hole for installing a temperature probe) were pre-drilled for each of the three target depths of measuring the MC along the thickness (see section 4.5). From the exterior surface of each panel, three sensors (two pairs of moisture pin sensors and one RH/T sensor, see section 4.5) were pre-installed, together with a wetting pad (see section 4.4). The exterior surface of each panel was afterwards covered with the self-adhesive, vapour-permeable membrane[6], which also partially covered the panel's four edges. The entire edges were then sealed with a continuous, self-adhesive, vapour impermeable membrane. This was intended to provide a separation of each test wall from its surrounding structure and to ensure that the moisture barrier would remain continuous and airtight throughout the panel.

The CLT panels were installed at the test hut by two professional installers, assisted with a forklift, from late August to early September 2020. Each panel was inserted into its assigned opening at a target depth to accommodate the exterior insulation to be installed. Once they were installed, the panels were fastened to their surrounding structural members using long screws. The gaps between the top/two sides of each panel and its surrounding structure, about 10 mm on average, were sealed with foam gaskets and tapes. The exterior insulation boards were subsequently installed to cover the panels on the exterior side. The reference light-wood-

[5] The cavity is just for concealing sensors and wiring; there is no insulation in this cavity.

[6] The membrane has a dry-cup vapour permeance of 629 ng/(Pa•s•m²) (about 11 Us perm) and a wet-cup vapour permeance of 972 ng/(Pa•s•m²) (about 17 Us perm), based on the manufacturer.

frame wall No. 3 was kept in place from the previous study; but the wetting pad on its OSB sheathing's exterior surface, together with its sheathing membrane and stone wool rigid exterior insulation were replaced with new materials from the exterior side. Efforts were made to ensure the exterior faces of all the five test walls would remain flush, allowing installation of continuous strapping and siding in both the north and the south orientations. The strapping, about 19 mm (nominal 1 in.) in depth using small dimension lumber, was to create a ventilated rainscreen cavity between the siding and the exterior insulation. The siding was painted hardboard recycled from the previous study. Inside the test hut, instruments were installed from September to December 2020. Afterwards, the walls were closed in, with the interior framing, the interior insulation (of walls No. 1 and No. 2), and the drywall installed in late January 2021. The painting on the drywall consisted of one coat of regular latex primer and two coats of latex top finish7, a common practice for new construction. Some photos in Appendix VI provide further information about the wall preparation and installation.

4.4 Wetting Pad

Building envelope failures in a wet climate, such as the coastal climate of BC are primarily caused by rainwater penetration. It was found a lack of drained and vented/ventilated cavities in exterior walls (e.g., behind cladding, around windows) was a major deficiency causing failures8 of hundreds of multi-unit residential buildings (wood, concrete) in the Lower Mainland approximately from 1985 to 1995 (CMHC 1996). Following that, a provision of a drained and vented cavity was incorporated into the 2005 NBCC for exterior walls in wet climates to minimize water penetration into the structure, the exterior sheathing (e.g., plywood, OSB) in particular. This solution has since been implemented well in construction practices, particularly in BC. But some recent evolutions in building envelope designs, particularly in response to the increasingly stringent energy efficiency requirements and popular use of various exterior insulation products may compromise its effectiveness since lower-permeance exterior insulation/membrane products have a large impact the drying capacity (Wang 2018). To assess in this study robustness of the test walls against external water leaks, it is planned to simulate exterior water leaks by injecting controlled amounts of liquid water into each wall assembly. A wetting pad, aimed to act as a water storage medium for facilitating moisture transmission into the wood, was installed on the exterior surface of each CLT panel (the OSB sheathing of wall No. 3), based on a method originally developed by Dr. John Straube and his team at the University of Waterloo (Smegal et al. 2012; Gauvin 2014; Trainor 2014). This external wetting pad was formed with two layers of shop-use paper towel, measuring about 275 mm (11 in., width) and 260 mm (10 in., height), and stapled on the exterior surface of each CLT (the OSB sheathing for wall No. 3) prior to installation of the external moisture barrier membrane (Figure 3).

In addition, it was decided to install a wetting pad on the interior surface of each CLT panel to potentially simulate interior water leaks (e.g., plumbing leaks) during the test. This internal wetting pad used instead thin cotton cloth, which was also highly vapour permeable to minimize its impact on the wall's hygrothermal performance. The change was made since the paper towel material used for the external wetting pad, without protection of a membrane, was not strong

[7] Products of Sherwin Williams

[8] The so-called "leaky condo" crisis in British Columbia

enough to resist the cyclic water injections to be conducted in the test. This internal wetting pad actually consisted of three vertical strips of cloth in order not to cover the moisture pin sensors installed from the interior surface, since direct contact with liquid water may affect the readings of the resistance-based moisture pins (section 4.5). However, the three pieces of cloth were joined from the top and between the sensors by stapling to ensure that the entire pad would become wet upon water injection (Figure 24). Nevertheless, investigation was needed to assess how uniformly water will transmit in both the depth and height directions of the CLT panels.

Each external/internal wetting pad was located at about ¼ of the wall height (i.e., with its top at a height of 24 in. (600 mm) from the bottom). A small plastic distribution tube, with an inside diameter of 6 mm (1/4 in.) was installed on top of each wetting pad. The tube had three small holes pre-drilled along the width of the wetting pad for uniformly distributing water to the wetting pad. One end of the tube was blocked, while the other was accessible from the interior of the test hut for injecting water. Based on the previous study as well as further trials, a reasonable protocol for simulating persistent external rainwater leaks under the test conditions would be to inject 10 mL water, twice a day, for two weeks or longer. The reduced amount of water/injection from the previous amount of 20 mL (Wang 2021) may ensure that the injected water would be completely absorbed first by the wetting pad and then transmitted to the wood, as opposed to running down. The previous study found this wetting mechanism overall functioned well, except for in the test walls incorporating rigid, low-vapour permeance exterior insulation boards (i.e., extruded polystyrene, foil-faced polyiso) that water ran down the exterior sheathing surface and passed the wetting pad (Wang 2021). The self-adhesive membrane used in this study may reduce the chance of water running down; nevertheless, a smaller dose would maximize water absorption by the wood panel.

Figure 3. A paper-based external wetting pad together with a plastic tube and sensors installed on the exterior surface of a CLT panel.

4.5 Instrumentation

A set of sensors including four pairs of RH/T and 14 pairs of MC/T sensors were installed in each CLT wall. The four RH/T sensors aimed to measure the environmental conditions including temperature and RH at mid-height across each wall. They were located from the interior to the exterior, including exterior to the drywall (inside the service wall cavity) of walls 1 and 2 and interior to the drywall of walls 4 and 5; interior to the CLT; between the external moisture barrier membrane and the CLT; and the rainscreen cavity (Figure 4). The RH/T sensors installed interior to the drywall of walls 4 and 5 would also serve to provide indoor environmental conditions for the other test walls.

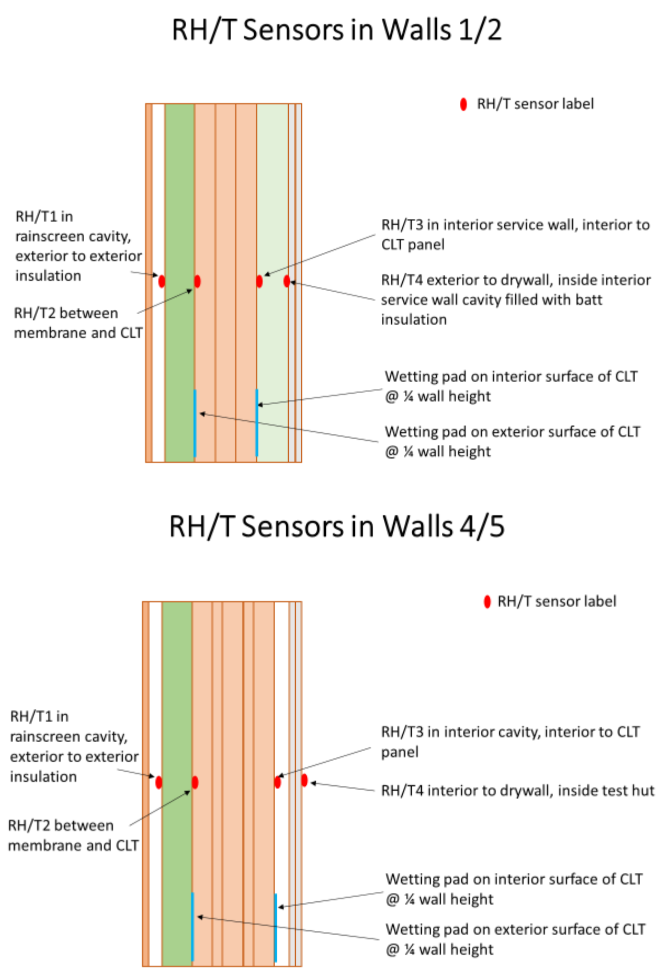


Figure 4. RH/T sensors installed at mid-height of walls 1 and 2 (left) and walls 4 and 5 (right) to measure environmental conditions across each assembly.

Sensors for measuring each CLT panel's MC were installed in two areas, the central area as a reference point (where the RH/T sensors were installed, without any impact of water injection) and the bottom wetting pad area. Each area included five measurement depths along the thickness of each CLT panel, including the exterior and the interior surfaces and three depths (targeting the mid-depth of the three thick laminas each, respectively) measured from the interior surface to assess MC profiles (Figure 5). Each set of MC measurement sensors consisted of a pair of moisture pins for measuring the electrical resistance between their two tips, together with a thermistor for correcting the temperature's effect on the MC readings (Garrahan 1988; James 1988; FPL 2010). The pins used in the surfaces were uninsulated stainless steel and inserted approximately 6 mm into the wood (to represent the wood's surface). The pins used at deeper locations were longer, insulated steel rods covered with plastic and had only with their tips exposed to be in contact with the wood. Except for the two sets of sensors pre-installed from the exterior surface during panel preparation (section 4.3), all other sensors were installed inside the test hut.

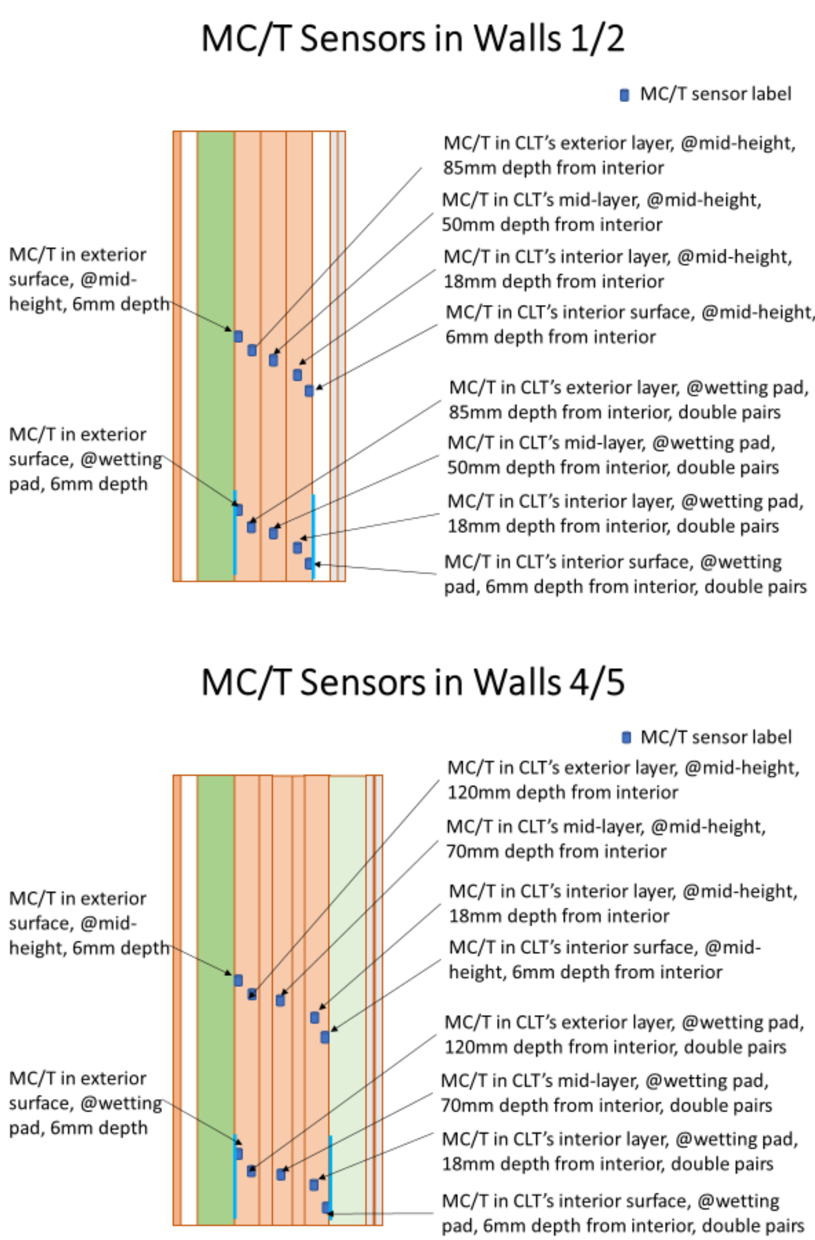


Figure 5. MC/T sensors installed in walls 1 and 2 (top, central) and in walls 4 and 5 (bottom, wetting pads) to measure wood moisture content across each CLT panel.

For the bottom wetting pad area, there were two MC measurement systems used, each with a replicate of four pairs of moisture pins installed from the interior surface for the four target depths, before the walls were closed in (Figure 6; Figure 7). The two systems, including an old wired one and a new wireless one, were installed side by side to improve measurement accuracy and redundancy. Many instruments used in this study were recycled from the previous study (Wang 2019a) to reduce costs. There was a concern about the old data logging system that it has a relatively high lower limit for measuring wood MC (e.g., a lower limit of MC of 11.4% for white spruce used in the previous study), resulting from its inherent lower cap for accurately measuring electrical resistance. This limitation could conceal valuable wetting and drying information about CLT given the fact that the test panels, especially of walls 4 and 5 are located adjacent to the indoor warm and dry environment with a target operational condition of 50% @ 20°C. Under such conditions, wood will achieve an average MC of approximately 10% (FPL 2010), very likely below the lower measurement limit of the old instrumentation system. The new data logging system, with a much higher cap for measuring electrical resistance was therefore selected and used for the crucial wetting pad area. But this system has its own disadvantages; for example, its readings are simply provided for “Douglas fir” at a temperature of 26.7°C (80°F), based on the calibration study conducted by the US Forest Products Laboratory (James 1988), which did not compensate the effect of temperature. Additional conversions and compensations are therefore required in order to correct the effects of both temperature and wood species.

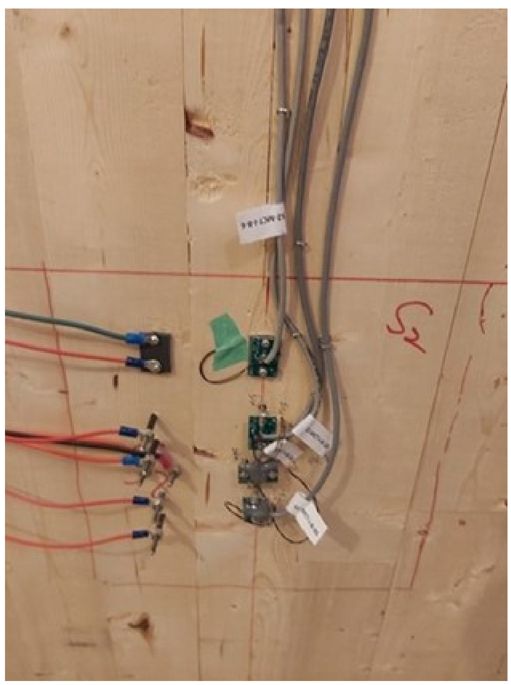


Figure 6. Two replicates of moisture pin sensors installed from the interior, side by side at the bottom wetting pad area for two data logging systems.

Figure 7. A photo to show the sensors (mid-height, bottom with the interior wetting pad) and wiring installed inside one wall panel (S2) with the interior service wall framed.

For reference No. 3 wall, the sensors installed in the previous study were simply kept in this study (Wang 2019a). Four RH/T sensors, labeled from RH/T1 to RH/T4, were installed as follows: in the exterior drained and vented space exterior to the exterior insulation; on the interior face of the OSB sheathing at mid-height (RH/T2); at about 475 mm from the bottom (i.e., interior to the exterior wetting pad, RH/T3); and exterior to the polyethylene sheet (RH/T4). Six pairs of moisture pin sensors, labelled from O1 to O6, were installed from the interior surface of the OSB sheathing at the same depth of about 6 mm but at various heights from top to bottom: 150 mm from the top; at mid-height (1200 mm from the bottom); 580 mm, 475 mm, and 360 mm from the bottom (these three sensors were installed on the interior side to the exterior wetting pad); and 150 mm from the bottom, respectively.

Three types of data loggers, 15 data loggers in total, were installed to collect data at 15 min intervals, which can then be averaged to obtain hourly readings.

4.6 Indoor Environment

Indoor humidity is part of the moisture loads that a building envelope has to manage. It was found to be the most important factor based on sensitivity analysis using hygrothermal modelling affecting the moisture performance of exterior sheathing in a mixed-humid climate (Glass 2013). The indoor humidity in a real building depends on the exterior environment (temperature, humidity etc.), ventilation rates, indoor moisture sources (breathing, cooking, washing, plants etc.), and moisture buffering capacity (e.g., desorption/adsorption of hygroscopic materials). Various modelling tools are available to simulate indoor humidity for hygrothermal simulations of building envelope assemblies (Glass and TenWolde 2009; Roppel et al. 2007a).

It was decided to maintain the indoor environment of the test hut under a target condition of 21°C and 50% RH9. This would generate an indoor vapour pressure of about 1240 Pa for the test walls. This target condition was created and maintained in the test hut by controlling the radiant heating system built into its floor and the operation of a humidifier (Aircare EP Series).

This target indoor condition was intended to represent the average or slightly higher indoor humidity found in Vancouver homes in the winter (Roppel et al. 2007b). FPInnovations' field monitoring has found indoor RH ranging from 25% to 65% in the Vancouver climate, with generally lower RH in the winter than in the summer10. The most recent monitoring study on an energy efficient six-storey wood-frame building found that the indoor RH mostly ranged from 30% to 40%, with the temperature of 20-25°C in seven selected suites in the winter (Wang 2019b). It is known that RH measurements typically have higher levels of uncertainty than measuring temperature, and most humidity sensors have a range of accuracy from ±3% to ±5% RH (Appendix V). The RH/T sensors used were found to be reasonably accurate by generating measurements very close to those by a high-precision handheld calibration meter (Vaisala HUMICAP® HM70).

5 NEXT STEPS

- To maintain the indoor environment and to conduct periodic water injection to investigate moisture-related response and performance of these test walls;
- To measure material properties including density and vapour permeance (dry cup, wet cup) for the major materials (CLT, drywall with and without painting, insulation, and membranes) used to build the test walls;
- To enable study results to be compared to findings from other studies and to support hygrothermal modelling;
- To adjust the test plan (schedule etc.), if necessary, when sufficient data have been collected;
- To conduct hygrothermal modelling to compare with field measurements and to evaluate different scenarios (e.g., different assemblies, climates) affecting wall performance;
- To provide recommendations to improve the design and construction of energy efficient mass timber buildings.

[9] When the exterior environment has RH of 90% @ 5°C in the winter in Vancouver, the RH will drop below 40% when it is heated to 20°C based on a psychrometric chart.

[10] Unpublished monitoring data

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APPENDIX I: TEST WALL ASSEMBLIES

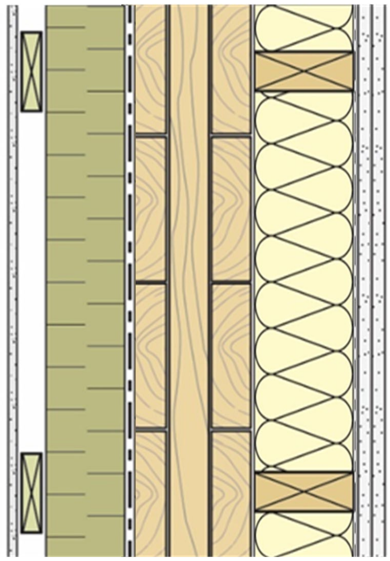

Figure 8. A schematic to show the assembly of test wall No. 1.

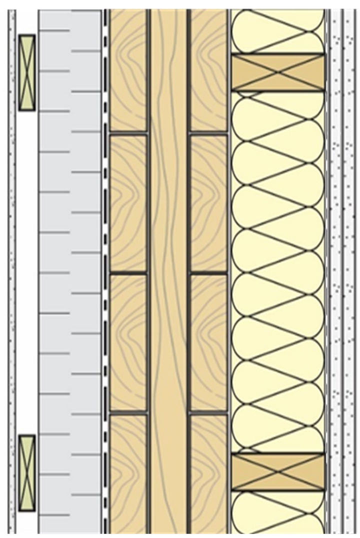

Figure 9. A schematic to show the assembly of test wall No. 2.

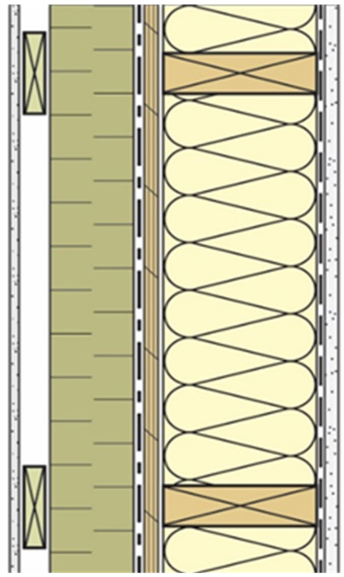

Figure 10. A schematic to show the assembly of test wall No. 3.

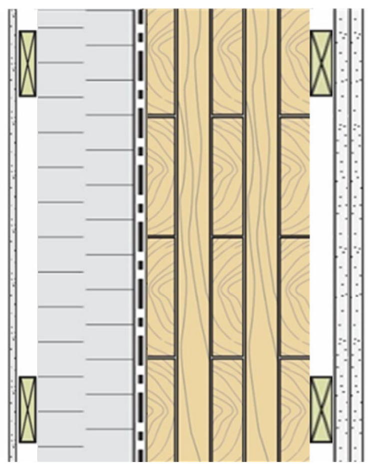

Figure 11. A schematic to show the assembly of test wall No. 4.

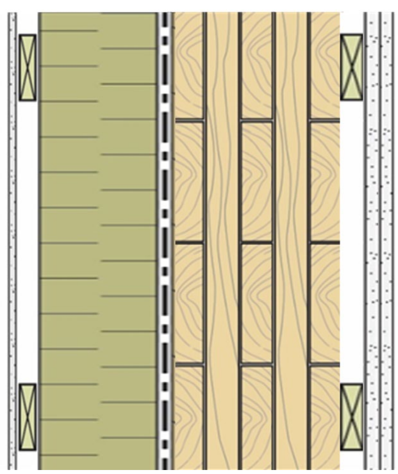

Figure 12. A schematic to show the assembly of test wall No. 5.

APPENDIX II: CALCULATION OF EFFECTIVE R-VALUES

Table 2. Calculation of effective R-values of six types of walls based on commonly used parameters.

Wall 1: CLT with 1.5" rigid stone wool insulation and an interior service wall				
Materials in assembly	**Material used**	**Material R-value**	**Thickness (mm)**	**RSI**
Outside air film				0.03
Siding	Wood hardboard		11	0.12
Air space (19 mm thick)			19	0.18
Exterior insulation	Rigid mineral wool, 3"	0.028	38	1.06
WRB membrane	Self-adhesive vapour-permeable membrane			0.00
CLT	3-layer (35mm/ply), 105 mm thick, S-P-F	0.0085	105	0.89
Interior service wall	2 by 4 with R-14 stone wool batt		89	1.62
Interior gypsum, double layer	Drywall with regular paint		25	0.16
Interior air film				0.12
Sum			287	4.19
Calculated Effective RSI				4.19
Calculated Effective R-value				23.78

Wall 2: CLT with 1" foil faced-polyiso insulation and an interior service wall				
Materials in assembly	**Material used**	**Material R-value**	**Thickness (mm)**	**RSI**
Outside air film				0.03
Siding	Wood hardboard		11	0.12
Air space (19 mm thick)			19	0.18
Exterior insulation	Impermeably-faced polyiso rigid board (R-6.5/in.)	0.04507	25.4	1.14
WRB membrane	Self-adhesive vapour-permeable membrane			0.00
CLT	3-layer (35mm/ply), 105 mm thick, S-P-F	0.0085	105	0.89
Interior service wall	2 by 4 with R-14		89	1.62
Interior gypsum, double layer	Drywall with regular paint		25.4	0.16
Interior air film				0.12
Sum			274.8	4.27
Calculated Effective RSI				4.27
Calculated Effective R-value				24.24

Wall No. 3: 2x6 with R20 batt insulation with 1.5" rockwool exterior insulation, for reference				
Materials in assembly	**Material used**	**Material R-value**	**Thickness (mm)**	**RSI**
Exterior air film				0.03
Hardboard siding			11	0.12
Air space (18 mm thick)			10	0.18
Exterior insulation	1.5" rockwool rigid board (R-4/in.)		37.5	1.06

Wall No. 3: 2x6 with R20 batt insulation with 1.5" rockwool exterior insulation, for reference				
Materials in assembly	**Material used**	**Material R-value**	**Thickness (mm)**	**RSI**
WRB membrane	Self-adhesive vapour-permeable membrane			
Exterior sheathing	OSB, 7/16 in.		11	0.11
Wood framing	2 by 6 lumber, S-P-F	0.0085	140	
Cavity insulation	Fiberglass batt	R-19		
Combined batt and framing	$RSI_{effective}$ = 100/(framing rati/RSIf + cavity ratio/RSIc)			2.36
Interior vapour control layer	Polyethylene			
Drywall, one layer				0.08
Interior air film				0.12
Calculated Effective RSI				4.05
Calculated Effective R-value				23.02

Wall 4: CLT with 2" foil-faced polyiso exterior insulation and a small interior cavity				
Materials in assembly	**Material used**	**Material R-value**	**Thickness (mm)**	**RSI**
Outside air film				0.03
Siding	Wood hardboard		11	0.12
Air space (19 mm thick)			19	0.18
Exterior insulation	Impermeably-faced polyiso rigid board (R-13.1/2 in.)	0.04578	50.4	2.31
WRB membrane	Self-adhesive vapour-permeable membrane			0.00
CLT	5-layer, 143 mm thick, S-P-F	0.0085	140	1.19
Interior vapour control layer	No			0.00
Air space (19 mm thick)	Furring, 1" nominal, for accommodating water tube and sensors		19	0.18
Interior gypsum, double layer	Drywall with regular paint		25.4	0.16
Interior air film				0.12
Sum			264.8	4.29
Calculated Effective RSI				4.29
Calculated Effective R-value				24.34

Wall 5: CLT with 3" rigid stone wool exterior insulation and a small interior cavity				
Materials in assembly	**Material used**	**Material R-value**	**Thickness (mm)**	**RSI**
Outside air film				0.03
Siding	Wood hardboard		11	0.12
Air space (19 mm thick)			19	0.18
Exterior insulation	Rigid mineral wool, 3" R4/in)	0.0277	76.2	2.11
WRB membrane	Self-adhesive vapour-permeable membrane			0.00
CLT	5-layer, 143 mm thick, S-P-F	0.0085	140	1.19

Wall 5: CLT with 3" rigid stone wool exterior insulation and a small interior cavity				
Materials in assembly	**Material used**	**Material R-value**	**Thickness (mm)**	**RSI**
Air space (19 mm thick)	Furring, 1" nominal, for accommodating water tube and sensors		19	0.18
Interior vapour control layer	No			0.00
Interior gypsum, double layer	Drywall with regular paint		25.4	0.16
Interior air film				0.12
Sum			290.6	4.09
Calculated Effective RSI				4.09
Calculated Effective R-value				23.23

APPENDIX III: MATERIAL PROPERTIES

Table 3. Key properties of the materials used to build the test walls based on literature and manufacturers.

Material	Thickness, mm (in.)	Density, kg/m3(lbs/ft³)	Thermal resistance		Vapour permeance	
			RSI-value, (m²·K)/W	R-value, ft²·°F·hr/Btu	ng/Pa•s•m²	US Perm
CLT panel (S-P-F) (Alsayegh et al. 2013)	89 (nominal 4 in.)	445 (27.8)	0.84	4.77	18	0.31
	143 (nominal 6 in.)	445 (27.8)	1.35	7.66	12	0.21
Stone wool rigid exterior insulation	38 (1.5)	128 (8)	0.7	4	1768	30.8
Foil-faced polyiso	25 (1)	40 (2.5)	1.1	6.24	lower than 15 (dry-cup)	0.3 (dry-cup)
Self-adhesive membrane	0.2 (0.008)	-	-	-	629 (dry-cup) 972 (wet-cup)	11 (dry-cup) 17 (wet-cup)
Interior gypsum board with latex primer and paint	12.7 (1/2)	700 (43.8)	0.08	0.45	580 (Glass 2013) 500 (Wang 2021)	10 (Glass 2013) 9 (Wang 2021)

*The properties provided for the insulation materials were extracted from manufacturers' information and based on 25 mm thick material.

APPENDIX IV: LOCATIONS OF SENSORS IN TEST WALLS

Table 4. List of sensors installed in each CLT-based test wall.

Sensor type	Purpose	Location of sensor
Combined MC and temperature for walls 1 and 2	Measuring MC, corrected with temperature, at the mid-height central area All sensors were inserted from the interior surface except for those on the exterior surface.	Interior surface (6 mm in depth)
		Interior layer of CLT (18 mm from interior surface)
		Middle layer of CLT (50 mm from interior surface)
		Middle layer of CLT (85 mm from interior surface)
		Exterior surface (6 mm in depth)
	Measuring MC, corrected with temperature, at the wetting pad area All sensors were inserted from the interior surface except for those on the exterior surface.	Interior surface (6 mm in depth), double pairs
		Interior layer of CLT (18 mm from interior surface), double pairs
		Middle layer of CLT (50 mm from interior surface), double pairs
		Middle layer of CLT (85 mm from interior surface), double pairs
		Exterior surface (6 mm in depth)
Combined MC and temperature for walls 4 and 5	Measuring MC, corrected with temperature, at the mid-height central area All sensors were inserted from the interior surface except for those on the exterior surface.	Interior surface (6 mm in depth)
		Interior layer of CLT (18 mm from interior surface)
		Middle layer of CLT (70 mm from interior surface)
		Middle layer of CLT (120 mm from interior surface)
		Exterior surface (6 mm in depth)
	Measuring MC, corrected with temperature, at the wetting pad area All sensors were inserted from the interior surface except for those on the exterior surface.	Interior surface (6 mm in depth), double pairs
		Interior layer of CLT (18 mm from interior surface), double pairs
		Middle layer of CLT (50 mm from interior surface), double pairs
		Middle layer of CLT (85 mm from interior surface), double pairs
		Exterior surface (6 mm in depth)
		Interior surface (6 mm in depth)
Combined RH and temperature for walls 1 and 2	Measuring the ambient environment including temperature and RH across each wall panel	Sensor "RH/T1", in the rainscreen cavity, at mid-height
		Sensor "RH/T2", between membrane and CLT, at mid-height
		Sensor "RH/T3", interior to CLT, at mid-height
		Sensor "RH/T4", exterior to drywall, in interior service wall cavity
Combined RH and temperature for walls 4 and 5	Measuring the ambient environment including temperature and RH across each wall panel	Sensor "RH/T1", in the rainscreen cavity, at mid-height
		Sensor "RH/T2", between membrane and CLT, at mid-height
		Sensor "RH/T3", interior to CLT, at mid-height
		Sensor "RH/T4", interior to drywall, measuring temperature and RH inside test hut
Total number of sensors		

APPENDIX V: INFORMATION OF SENSORS

Table 5. Sensors installed in the test wall panels.

Purposes	Instrument	Shape and size	Note
Measuring environmental relative humidity (RH) and temperature (T)	Combined RH and T sensors, called "RH/T" sensors	Small probes	RH resolution: 0.5%; Accuracy: ±3% to ±5% (in the range of 10-95%) Temperature tolerance: 1%; Resolution: 0.1°C; Accuracy ±1°C
Measuring wood MC	Resistance-based moisture pin sensors	Small screws	Steel pins in contact with wood
Collecting and transferring data wirelessly	Data loggers for RH/T sensors, wireless module	Data logger box: 125 mm × 125 mm × 64 mm	Measurement Specifications Internal Temperature Sensor: Cantherm MF58104F39590 Beta 4390K Range: -40°C to +70°C Resolution: 0.1°C Accuracy: ±1°C Internal Relative Humidity (optional) Sensor: Honeywell HIH-4000-001 Interchangeability: 0-59% RH ±5% 60-100% RH ±8% Resolution: 0.5% RH Accuracy: ±5% RH Hysteresis: 3% RH Repeatability: ±0.5% Resistance Range: 10Ω to 100Ω Resolution: 1Ω Accuracy: ±5% Range: 100Ω to 100KΩ Resolution: 10Ω Accuracy: ±1% Range: 100KΩ to 1GΩ Resolution: 1KΩ Accuracy: ±5% Voltage Range: 0Vto5V Resolution: 100mV Accuracy: ±5%
Collecting and transferring data wirelessly	Data loggers for MC/T sensors, wireless module	MultiScan boards	Resistance – Inputs 1-48 Range: 100Ω to 1KΩ Resolution: 10Ω Accuracy: ±5% Range: 1KΩ to 10KΩ Resolution: 100Ω Accuracy: ±5% Range: 10KΩ to 100KΩ Resolution: 1KΩ Accuracy: ±5% Range: 100KΩ to 1MΩ Resolution: 10KΩ Accuracy: ±5%

Purposes	Instrument	Shape and size	Note
			Range 1MΩ to 10MΩ Resolution: 100KΩ Accuracy: ±5% Range: 10MΩ to 100MΩ Resolution: 1MΩ Accuracy: ±10% Range: 100MΩ to 1GΩ Resolution: 10MΩ Accuracy: ±10%
Collecting and transferring data wirelessly	Data loggers for MC/T sensors, wireless module	Small boxes	Standard accuracy (±0.4°C/±3.5%RH) ±0.3°C/±2.0%RH

APPENDIX VI: PICTURES TAKEN DURING CONSTRUCTION AND INSTRUMENTATION

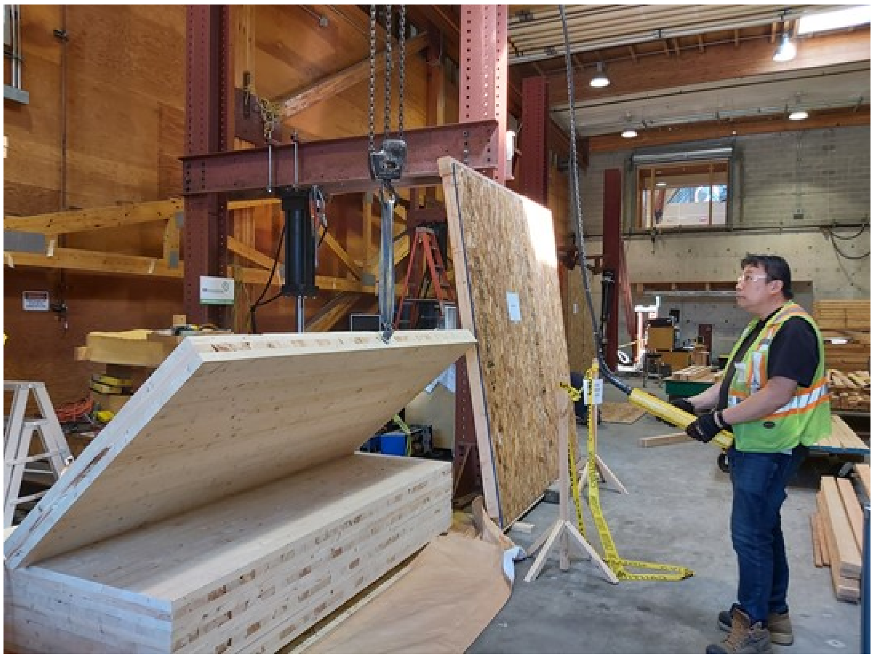

Figure 13. CLT panel being lifted for pre-preparation.

Figure 14. CLT panel being pre-prepared for instrumentation and assembly.

Figure 15. CLT panel covered with a self-adhesive, vapour-permeable membrane, with four edges sealed with an impermeable membrane.

Figure 16. Piles of pre-prepared CLT panels prior to site installation.

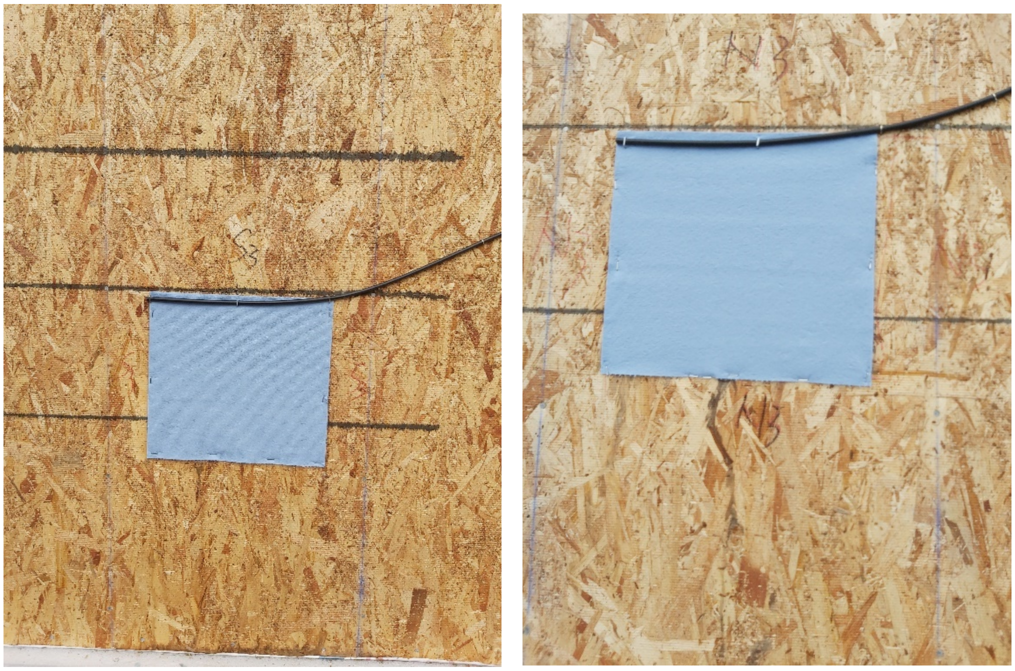

Figure 17. A new wetting pad fed with a water tube installed on the exterior surface of the OSB sheathing of wall 3 (left: S3; right: N3).

Figure 18. All test wall panels installed at the test hut.

Figure 19. An RH/T sensor installed in the rainscreen cavity of each wall.

Figure 20. The exterior surface kept flush for installing continuous strapping and siding.

Figure 21. The exterior completed.

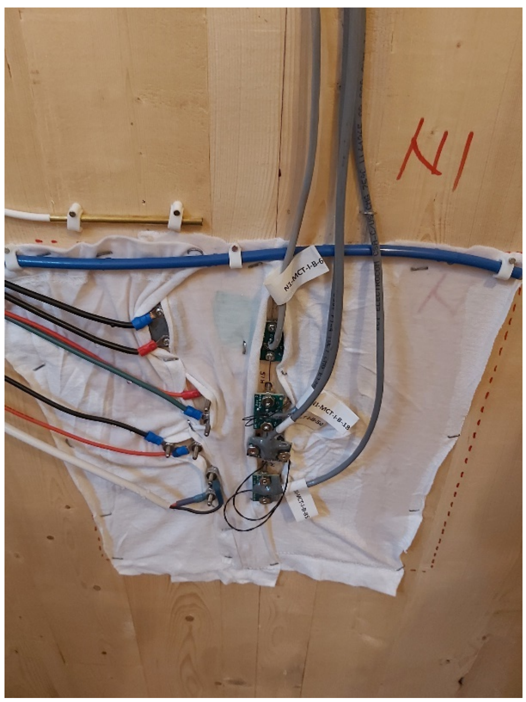

Figure 22. The bottom moisture pin sensors installed from the interior surface of each CLT panel covered with cotton cloth as a potential internal wetting pad.

Figure 23. Stone wool batt insulation (nominal R14) installed to cover sensors installed from the interior surface of CLT.

Figure 24. Stone wool batt insulation installed in the interior service wall cavities of walls No.1 and No. 2.

Figure 25. The edges (including those of drywall) of each wall sealed with a tape.

Figure 26. Each wall painted with a regular primer and two coats of top finishing.

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