Hygrothermal Analysis of Cross-Laminated Timber (CLT) in Canadian Climates With and Without Adhesive Layers Using a 1D-HAM Numerical Modelling Tool

D. Johns, Y. Vyas, R. Richman, and Z. Liao

1 Introduction

As the effects of climate change progress, there has been an increase in the interest and development of sustainable infrastructure in the construction industry. Mass timber, a type of engineered wood product, is a sustainable construction material with a significantly lower carbon footprint compared to conventional construction materials such as concrete and steel [3, 11]. Cross-laminated timber (CLT) is a type of mass timber product and is manufactured by adhering layers of orthogonally oriented wood boards to form a large structural component [11]. CLT products are composed primarily of wood, which is an organic hygroscopic material [8] and is therefore highly susceptible to biodegradation, physical deterioration and dimensional changes depending on localized temperature and moisture conditions [4, 11–13, 15].

A numerical hygrothermal model enables the prediction of short- and long-term durability and performance of CLT [2, 5, 9]. Using the 1D-ODE HAM hygrothermal modelling tool developed by Vyas et al. [16], this study will analyze the impact of climate variations in specified Canadian locations on the performance and durability of 3-layer and 5-layer CLT within exterior enclosure assemblies. The novel modelling tool includes the impact of adhesive layers on the overall performance of CLT, thereby generating higher accuracy and reliability of results as they relate to the properties

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of the actual material and the material's specific layers. In order to simulate realistic temperature and moisture conditions on either side of the CLT, the CLT has been modelled within a typical wall assembly [16] composed of insulation, a vapour permeable air barrier and wood cladding typical in the cold climates of all locations studied.

The performance of CLT incorporated within a building enclosure depends on exterior and interior conditions [5, 6, 9–11]. The exterior climatic conditions vary with location and time, as a result, an accurate localised weather condition file is essential to model the hygrothermal performance of the building enclosure. Ideally, the weather files should allow the designs to also stress test the building envelope by considering atypical and severe climate conditions. Due to the increase in global temperatures and atypical weather conditions, the Actual Meteorological Year (AMY) and Typical Meteorological Year (TMY) files represent vastly different weather conditions [7]. To account for these differences, this study will use both AMY and TMY climate datasets in separate simulations to evaluate the performance of CLT depending on the location and the climate dataset type.

It is understood that the hygrothermal performance of the CLT will vary depending on the location, where colder climates will perceive larger variations in temperatures and coastal climates will perceive larger variations in moisture content. In the case of greater moisture content variations, it is expected that adhesive layers will have a greater impact on minimizing the higher volume of moisture transport into internal wood layers of the CLT compared to locations with low moisture content variations.

2 HAM Model Development

Heat, air, and moisture (HAM) processes are modelled using 1D ODE equations in Matlab and Simulink. The lumped model assumes a single node per layer or slice of a material, which is impacted by adjacent nodes [16]. Temperature and moisture content of all layers are uniformly distributed [16]. Conduction, through direct contact of materials, convection, natural ventilation and infiltration, and radiation are considered for modelling heat transfer through the model. The model uses temperature and relative humidity to process the indoor and outdoor environmental conditions.

2.1 Integration of Climate Data

In order to account for variability between typical and actual weather conditions in any location, both Typical Meteorological Year (TMY) and Actual Meteorological Year (AMY) datasets will be integrated in the 1D HAM model. TMY data accounts for longer periods, typically between 15 and 30 years and uses weighted averages of all weather conditions [7] (https://climate.weather.gc.ca). AMY data only accounts for a single year period of actual weather data and can also be used to cross-check and stress-test the performance of buildings, building assemblies and building materials [7] (https://climate.weather.gc.ca).

For the purposes of this study, climate data in the form of TMY and AMY climate datasets have been gathered for five Canadian cold climate locations: Toronto, ON, Vancouver, BC, Calgary, AB, Yellowknife, NWT, and Halifax, NS. Although all locations are still considered to be cold climates, they vary significantly in temperature and humidity throughout the year. In order to simulate realistic weather conditions at each location within the 1D-ODE HAM model, the following weather data is required to be extracted from TMY and AMY datasets: temperature, relative humidity, radiation, sun angle, and air velocity. Each of these weather-related climate conditions will impact the hygrothermal performance of the assembly incorporating CLT.

Climate data for TMY and AMY was gathered from Energy Plus Weather (EPW) files, and the Canadian Weather Energy and Engineering Datasets (CWEEDs), respectively, The TMY files represent averages of the yearly climate data [7]. For the models developed in this study, the TMY datasets are representative of climate data gathered between 1961 and 1990. The CWEEDs have been gathered from 1998 to 2017 for 564 Canadian locations (https://climate.weather.gc.ca). This study is based on 2017 AMY weather datasets obtained from the open source Engineering Climate Datasets collection from the Government of Canada's website (https://climate.weather.gc.ca).

3 Methodology

The model used for this study was developed by Vyas et al. [16], using a novel approach to analyze CLT performance in various climates. In this study, the model was validated and calibrated using WUFI, a well-established hygrothermal software.

3.1 Simulation Variables and Permutations

In order to provide a full comparative analysis, 6 variables were tested at each location: TMY Climate Data, AMY Climate Data, 3-layer CLT, 5-layer CLT, and the presence or absence of adhesive layers in the 1D-ODE HAM model. The combination of these variables at each of the 5 locations results in 40 different permutations. Figure 1 diagrams all of the permutations for one location.

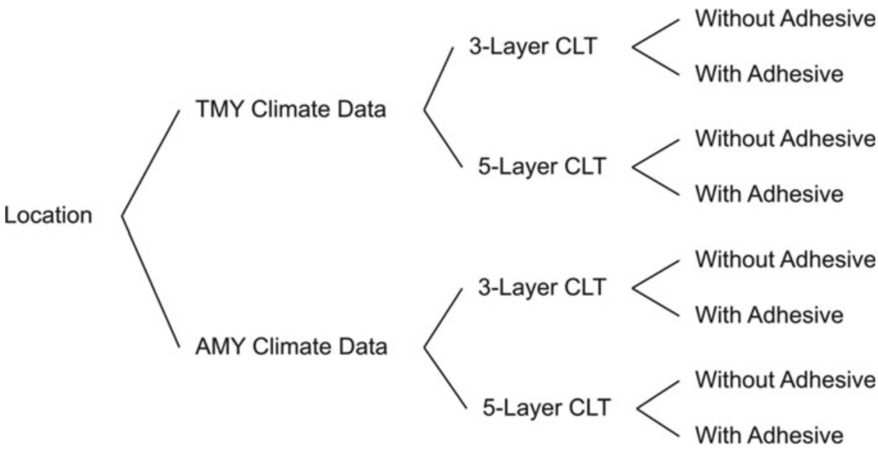

Fig. 1 Simulation variables and permutations at each location

3.2 Assembly and Node Configuration

A consistent wall assembly incorporating each permutation of CLT panel at each location was modelled in the 1D-ODE HAM model [16]. This assembly represents a typical cold climate wall assembly incorporating CLT and is composed of the following materials (from exterior to interior): wood cladding, vapour permeable air barrier, XPS insulation, and CLT [16]. The inclusion of an air space has been negated due to its negligible effects on heat and moisture transfer. The incorporation of CLT as the structural layer in this typical assembly enables the generation of realistic temperature and humidity results at both faces of the CLT [16] based on AMY and TMY climate data of the simulation locations.

The 1D-ODE HAM model developed in Matlab and Simulink by [16] and used in this study is based on a lumped model where the layer, or specific slice of a material, has one temperature and moisture content. Each layer or slice of a material is represented in the model by a node, where each node represents the centre of the volume of that layer or slice of material. Each layer is impacted by adjacent layers, and there is constant thermal and moisture transfer through the assembly layers as these processes work to achieve equilibrium between the indoor and outdoor environments [9, 16] . Governing 1D HAM equations were used to model the heat, air, and moisture transfer through an assembly; all equations are all correlated, and all processes influence the overall HAM model through internal dependency [16].

The 1D-ODE HAM model can simulate 3-layer and 5-layer CLT panels with separate wood and adhesive layer nodes depending on its configuration. Due to the high moisture permeance of the wood layers compared to the adhesive layers [16], each wood layer has been subdivided into two modelled layers to increase the accuracy of the model. Figure 2 illustrates the 3-layer CLT and 5-layer CLT assemblies and their node configurations including and not including adhesive layers.

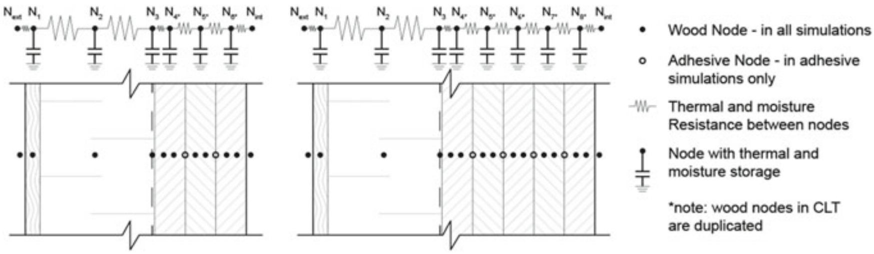

Fig. 2 Node configuration in 3-layer CLT and 5-layer CLT assemblies with and without adhesive layers [16]

3.3 Model and Simulation Assumptions and Outputs

The simulation results relevant to determining the hygrothermal performance and long-term durability of each CLT sample in each location are temperature, relative humidity, and moisture content. These outputs will be taken from the nodes of the CLT panel in each simulation for analysis.

The comparative analysis will be structured based on the 40 permutations described in Sect. 3.1 and will focus on the moisture content values extracted from the CLT nodes in order to determine if any conditions are generated within the CLT which could cause degradation through biological deterioration, dimensional instability, and/or physical deterioration. Further simulations will be described and performed as determined by the initial comparative results of the first 40 permutations.

The material characteristics (i.e. thermal conductivity, vapour permeability, moisture sorption curve, and suction pressure) were gathered directly from WUFI, as WUFI was used to validate the 1D-ODE HAM numerical modelling tool. Interior temperature and relative humidity (RH) were modelled at 20°C and 40% RH in winter and 24°C and 60% RH in summer. Based on literature reviewed [1, 14, 16], as well as a crack flow and model sensitivity analysis conducted by [16] comparing Simulink and WUFI results, the air change per hour (ACH) is assumed to be 1 ACH.

A sample 1 m × 1 m wall assembly was modelled to evaluate the hygrothermal performance of the CLT in the Simulink model. The wall assembly remained consistent for each simulation except for the properties of the CLT which differ according to the 6 variables established in Fig. 1. The initial RH values of each material node throughout the assembly were modelled at 80% RH in order to perceive initial drying behaviour of the wood over the first year simulated.

4 Results

4.1 Initial Temperature and Relative Humidity Results

The temperature profiles for all simulations are not shown in this paper as the results indicate that the adhesive layers do not have any impact on the thermal performance of the 3-layer or 5-layer CLT. This was expected due to the negligible thermal properties of the adhesive layers. Considering similar boundary conditions, the middle nodes of the 5-layer CLT will have fewer and more gradual temperature fluctuations than the 3-layer CLT, this is due to the thermal resistance and capacity of the wood.

The relative humidity profiles for all simulations are not shown in this paper because moisture content is directly related to RH and because all standards for the manufacturing and service of CLT are based on moisture content values. Therefore, for the purposes of this study, the simulation results shown and analyzed are of moisture content values only.

4.2 Initial Moisture Content Results

The moisture content (MC) profiles shown in Figs. 3, 4, 5, 6, 7, 8, 9 and 10, are taken from the average MC results of the centre two wood nodes in both the 3-layer and 5-layer CLT. These profiles therefore represent the moisture content in the centre layer (node) of wood in the 3-layer and 5-layer CLT.

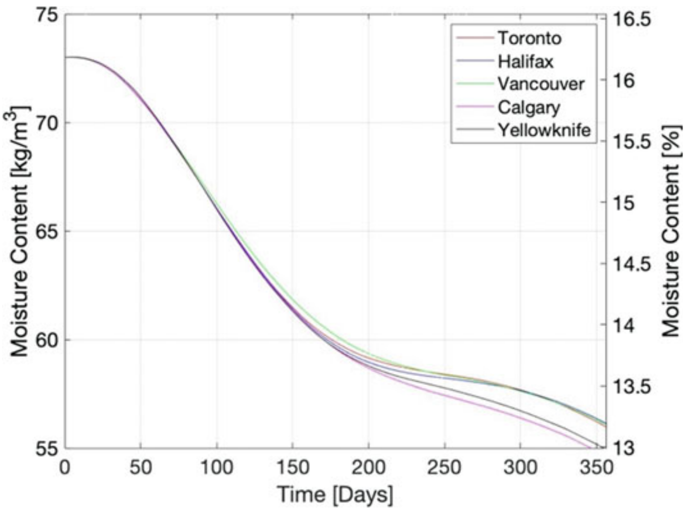

Fig. 3 Moisture content in centre wood nodes of 3-layer CLT without adhesive layers at each location using TMY climate data

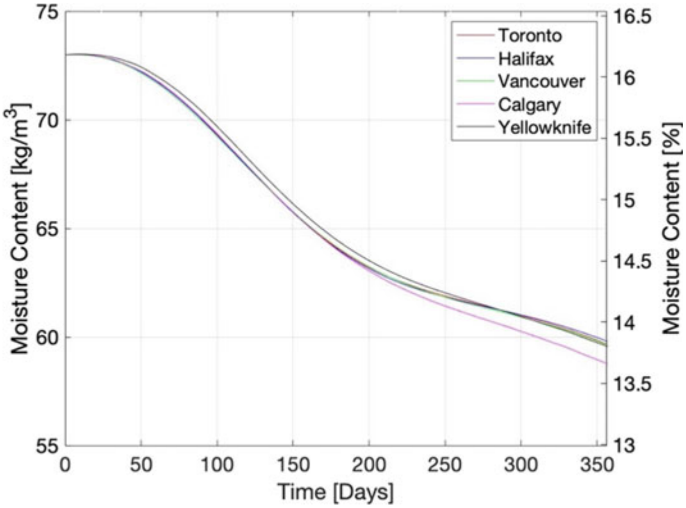

Fig. 4 Moisture content in centre wood nodes of 3-layer CLT with adhesive layers at each location using TMY climate data

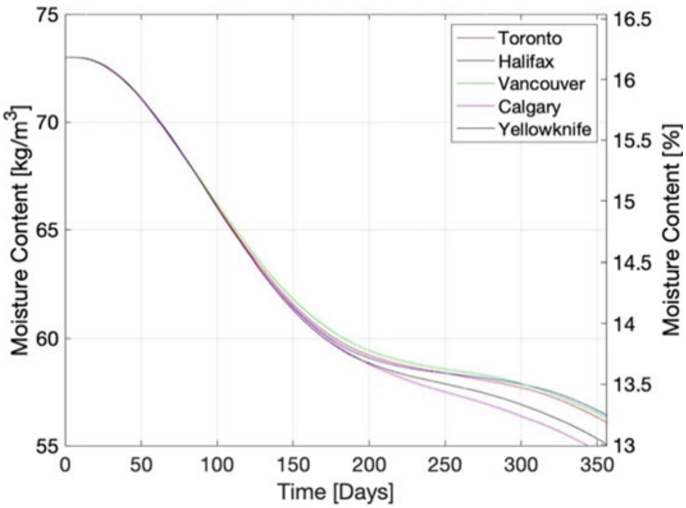

Fig. 5 Moisture content in centre wood nodes of 3-layer CLT without adhesive layers at each location using AMY climate data

From the initial MC results shown in Figs. 3, 4, 5, 6, 7, 8, 9 and 10, the results of the centre nodes of 3-layer CLT compared to 5-layer CLT show a faster decrease in MC. This was expected due to the fewer number of wood and adhesive layers on either side of the centre layer of wood in 3-layer CLT versus 5-layer CLT. Additionally, the results shown in simulations with adhesive layers versus without adhesive layers

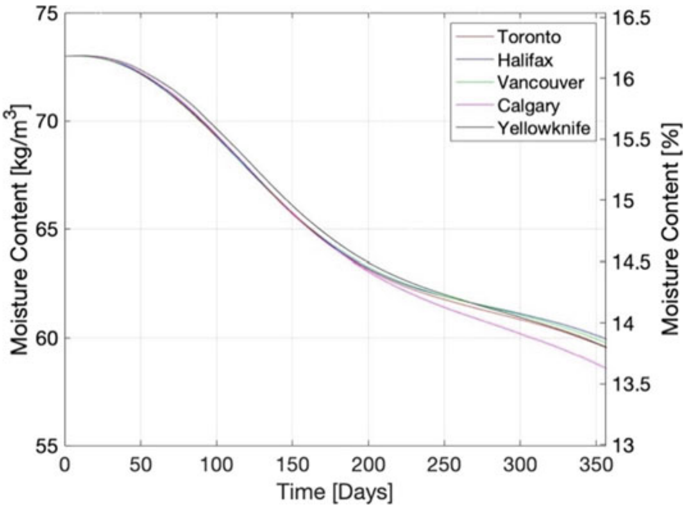

Fig. 6 Moisture content in centre wood nodes of 3-layer CLT with adhesive layers at each location using AMY climate data

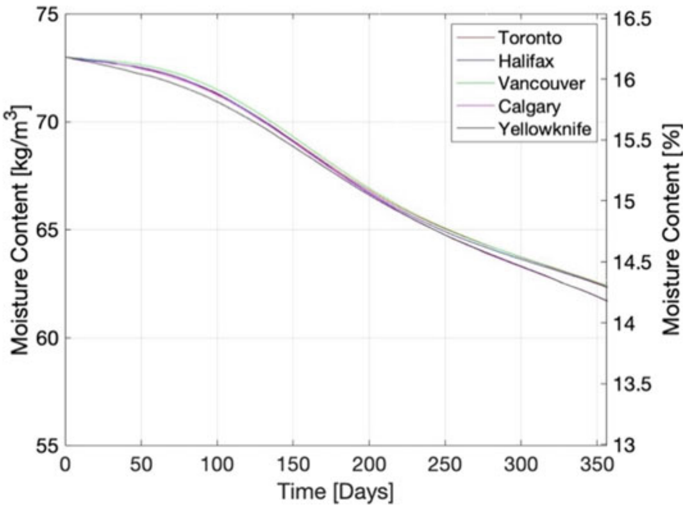

Fig. 7 Moisture content in centre wood nodes of 5-layer CLT without adhesive layers at each location using TMY climate data

confirm that the adhesive layers impact the MC in the centre of the CLT. The impact of adhesive layers is indicated by higher MC values and slower rate of decreasing MC (longer dry-out period) in the simulations which include adhesive layers.

From the initial results, it is clear that the difference between simulating the MC in any variable combination of CLT with AMY climate data versus TMY climate

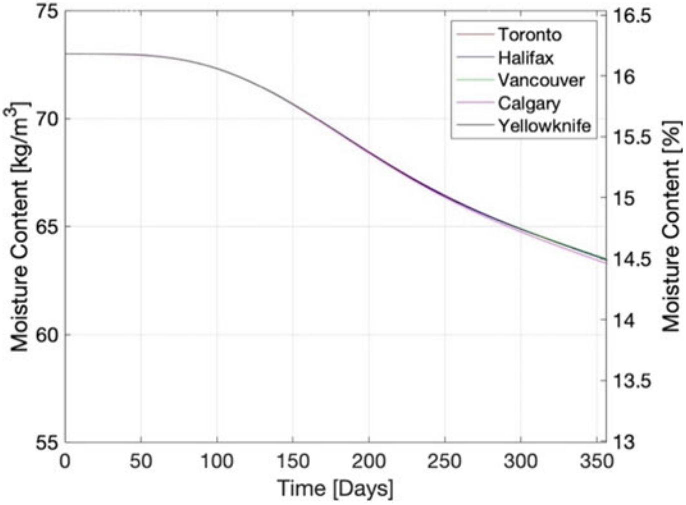

Fig. 8 Moisture content in centre wood nodes of 5-layer CLT with adhesive layers at each location using TMY climate data

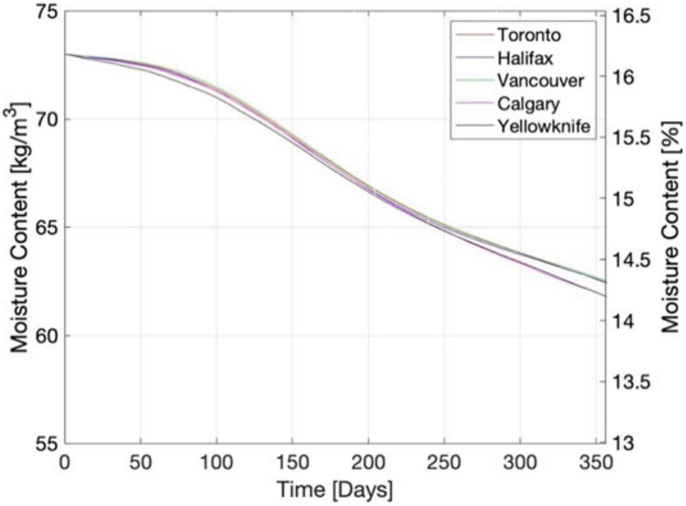

Fig. 9 Moisture content in centre wood nodes of 5-layer CLT without adhesive layers at each location using AMY climate data

is negligible. Therefore, the following results and comparison will use TMY data only and will focus on comparing the MC in each wood layer of 3-layer and 5-layer CLT in two of the climate conditions: Calgary and Vancouver. These locations were selected due to their inherently opposing climatic conditions as well as the variation in MC results in the initial simulations.

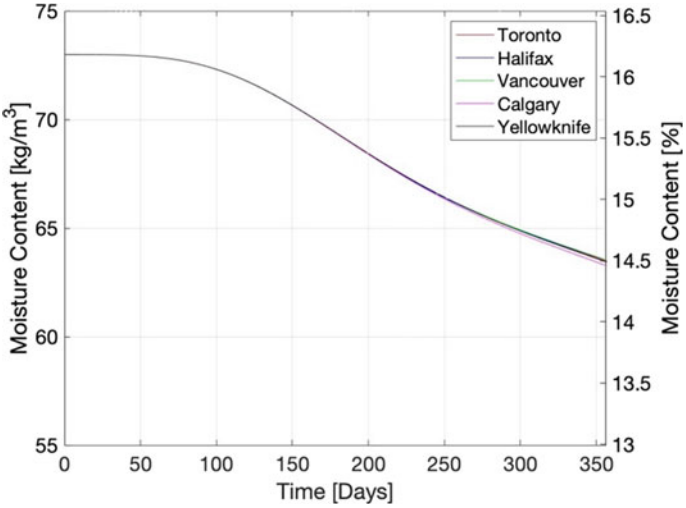

Fig. 10 Moisture content in centre wood nodes of 5-layer CLT with adhesive layers at each location using AMY climate data

4.3 MC Comparisons Between Each Wood Layer in Calgary and Vancouver

As discussed, the following results will focus on comparing the MC in each wood layer of 3-layer and 5-layer CLT. This analysis will visualize the impact of the adhesive layers on the MC in each wood layer and will also demonstrate the impact of climate conditions on the MC in each wood layer. Refer to Fig. 2 for layer number locations within the 3-layer and 5-layer assemblies.

The MC profiles in Figs. 11 and 12 indicate that there is little variation in layers 5 and 6 (centre and interior wood layers, respectively) between Calgary and Vancouver in the 3-layer CLT being simulated. However, layer 4 (the outermost layer of wood) shows elevated moisture content with and without adhesive layers in Vancouver compared to Calgary due to the elevated moisture and relative humidity conditions in a TMY in Vancouver. This would indicate that the outer layers of wood and adhesive layers regulate the moisture content in the centre layer of wood in 3-layer CLT.

Similar to the results of the 3-layer CLT illustrated in Figs. 11 and 12, the MC profiles of the 5-layer CLT, shown in Figs. 13 and 14, indicate that there is little variation in the centre and interior layers of wood (layers 5, 6, and 7) between Calgary and Vancouver. Also analogous to the 3-layer CLT results, the outermost layer of wood is most influenced by the exterior climatic conditions in 5-layer CLT. The climate conditions therefore, have a negligible impact on the moisture transfer in both 3-layer and 5-layer CLT. However, the comparison between moisture transfer with and without adhesive layers between 3-layer and 5-layer CLT varies significantly.

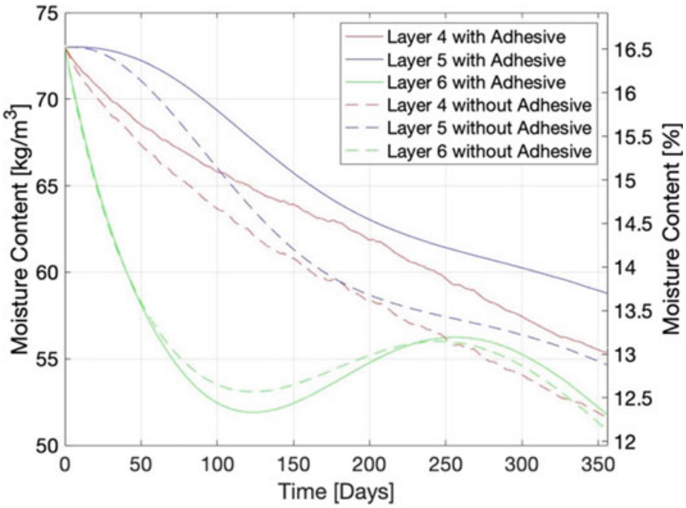

Fig. 11 Moisture content in each wood layer of 3-layer CLT with and without adhesive layers in Calgary using TMY climate data

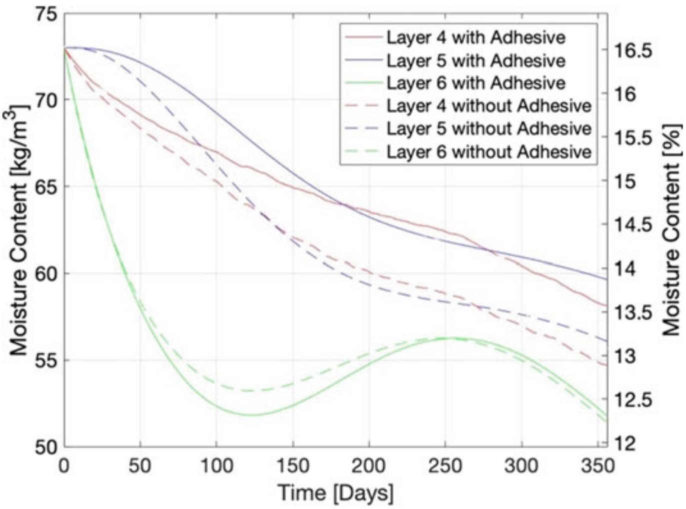

Fig. 12 Moisture content in each wood layer of 3-layer CLT with and without adhesive layers in Vancouver using TMY climate data

Comparing the outer layer only between 3-layer and 5-layer CLT indicates that in 5-layer CLT the inclusion of adhesive layers increases the drying rate of the outer wood layer, whereas in 3-layer CLT the inclusion of adhesive layers decreases the drying rate of the outer wood layer. This paradox can be explained by the moisture storage capacity of the additional wood layers in 5-layer CLT. Because all wood layers

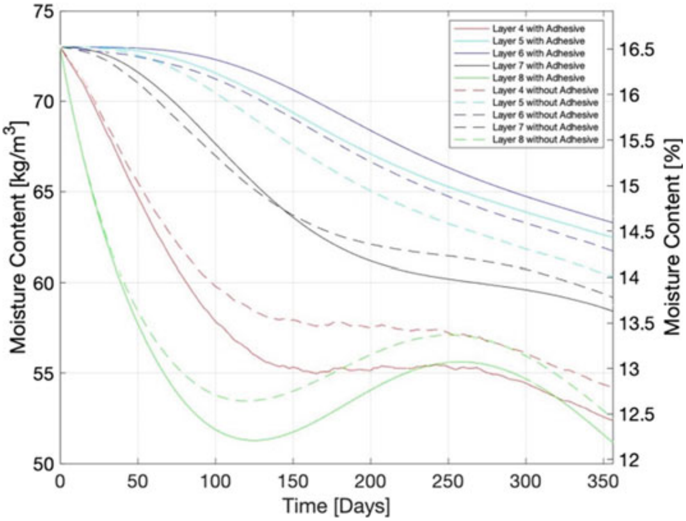

Fig. 13 Moisture content in each wood layer of 5-layer CLT with and without adhesive layers in Calgary using TMY climate data

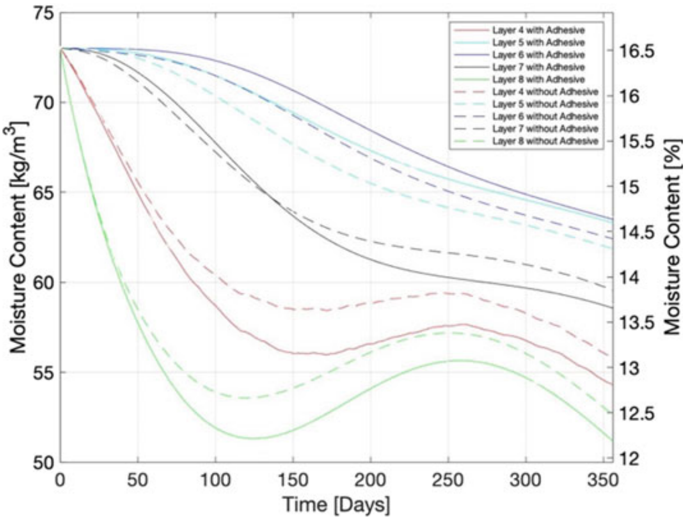

Fig. 14 Moisture content in each wood layer of 5-layer CLT with and without adhesive layers in Vancouver using TMY climate data

begin at the same moisture content (16.5%), and are effectively drying over the first year simulated, the moisture content stored in the additional wood layers on either side of centre layer in 5-layer CLT effectively act as hydraulic buffers increasing moisture content in the outer layers at a faster rate when adhesive layers are not included. Including adhesive layers in the 5-layer CLT simulations therefore decreases the rate at which the additional interior wood layers can dry out. The relationship between including adhesive layers in 3-layer versus 5-layer CLT is therefore inversely related in the outer layers of wood.

5 Conclusions and Future Research

The results referenced and included in this study were simulated using a novel 1D-ODE HAM numerical modelling tool developed by Vyas et al. [16]. This model enabled the assessment of the impact of climate conditions on the hygrothermal performance of 3-layer and 5-layer CLT, specifically including the impact of adhesive layers.

The results show that the climate conditions do not have as significant of an impact on the hygrothermal performance of CLT in service as anticipated. However, this could change drastically if the simulations were performed during construction and before the building is enclosed, when CLT has a higher level of exposure to typical and significant weather events.

During the comparison between 3-layer and 5-layer CLT the outermost layer showed an inverse relationship dependent on the inclusion of adhesive layers. This can be attributed to the additional wood layers in 5-layer CLT and their additional moisture storage capacity compared to 3-layer CLT.

Future research will include laboratory testing and long-term field testing to further validate the numerical modelling tool. Laboratory testing will be performed to determine specific hygrothermal characteristics of a range of CLT samples, including samples fabricated in-house. Long-term field testing will provide a foundation of real-time results to be compared with further laboratory results. Together, the laboratory and field testing will also enable further research related to moisture transfer in CLT depending on air tightness of the envelope and specific boundary conditions. As noted in the results of this study, the interior boundary conditions of CLT have the potential to impact the adjacent interior environment, opening future research to also include the buffering capacity of CLT. A high quantity and quality of experimental research and results are required to accurately calibrate and to potentially elevate the capabilities of the developed numerical modelling tool and to validate its predictive proficiency.

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