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THE HYGROTHERMAL PERFORMANCE AND DURABILITY OF A ONE-STORY CROSS-LAMINATED TIMBER AND WOOD FIBER INSULATION SCHOOL BUILDING LOCATED IN BELFAST, MAINE

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ABSTRACT: Decarbonization efforts as a result of the anthropogenic driven climate crisis are driving increased interest in bio-based building materials, including cross-laminated timber (CLT) and wood fiber insulation (WFI). These wood-based building materials can be used to increase energy efficiency and offer solutions that limit risk of interstitial condensation. WFI is a vapor-open, high specific heat, low embodied carbon insulation derived from fibrillated softwood chips. The hygroscopic nature of wood allows for seasonal moisture migration through the wall assembly, preventing liquid water accumulation within the envelope. The objective of this research was to monitor and evaluate the hygrothermal performance of a hybrid wood-based building envelope comprised of CLT and WFI. A one-story school building located in Belfast, ME (US Climate Zone 6A), was instrumented with temperature, relative humidity, and moisture content sensors during the manufacturing of the prefabricated wall and roof panels. Sensor clusters were installed at different locations within the wall and roof in both north- and south-facing orientations. In addition, an energy monitoring system was installed during the construction of the building to record the energy consumption of the school building; however, the results were not included in this study. Data was collected over a two-year period and was used to assess the temperature and relative humidity profile of the system, as well as validate a one-dimensional hygrothermal model. The model was then used to perform a long-term durability assessment. Results demonstrate that condensation and moisture accumulation have not occurred, while measured and simulated values agree. A long-term mold risk assessment found there to be no mold risk at any of the monitoring positions or interior surfaces.

KEYWORDS: Decarbonization, cross-laminated timber, wood fiber insulation, hygrothermal performance

1 – INTRODUCTION

The built environment is responsible for about 40% of total energy consumption in the United States [1]. In order to meet global emissions targets, an approximately 35% decrease in the operational energy consumption of buildings is required [1]. One solution to decrease energy consumption in the built environment is to increase the thermal performance of building envelopes, subsequently reducing heat transfer from interior and exterior conditions. This can be done through the addition or increase of thermal insulation, as well as utilization of materials with high specific heat capacities which stores heat energy before release, reducing temperature fluctuation. Using these principles, building envelopes have evolved significantly over the last century, improving the energy efficiency and comfort of buildings [2].

With this improvement in efficiency, there has been an increase in occupant health concerns. The term sick building syndrome (SBS) was first used by the World Health Organization (WHO) in 1983 and describes symptoms that are influenced by the indoor environment, including VOCs, molds, and air contaminants [3]. In response, consideration of mold growth and condensation risk increased. Natural materials are often assumed to be of greater risk than fossil-based counterparts due to nutrient availability and porosity. Mold can thrive on materials derived from wood having a moisture content between 30 and 150%, a temperature between 0 and 40 °C, and accessible nutrients. However, natural materials are often vapor open and have good drying potential, which allows water vapor to pass through and prevents

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accumulation when used properly within a system [4]. This, in turn, can reduce the risk associated with these materials, however, performance assessment is necessary and should always be conducted.

Current methods of envelope improvement often employ non-renewable structural and insulation materials. Alternatively, cross-laminated timber (CLT) and wood fiber insulation (WFI) are two materials that act as carbon sinks during the lifetime of the building while meeting thermal and structural requirements when used in a hybrid system [5, 6]. These materials can be used to reduce anthropogenic impact on global ecosystems while creating new and updating existing infrastructure [7].

CLT and WFI were developed in European nations during the late 1900s, however they remain niche products within the North American market. Much of this can be attributed to greater costs associated with the introduction of new materials, education, and difficulties of operating within new supply chains [8]. Although there is increasing interest, there remain a limited number of instances where either material is used in diverse North American climates.

In-situ monitoring of hygrothermal parameters within existing structures is a direct method of assessing material and system performance. This can provide building owners with performance data, as well as an assessment of long-term durability of the system [9]. Monitoring can reduce uncertainty that comes from simulation, however, monitored data can be used to validate a hygrothermal model.

Hygrothermal models are important tools for building envelope analysis. One such tool is WUFI, a hygrothermal simulation tool that has been widely validated [10, 11]. The one-dimensional tool, WUFI Pro 7.0, calculates transient coupled heat and moisture transport through opaque assemblies. This tool has been used to assess wood-frame walls, masonry walls, and High-R value wall assemblies [12-14]. A review of the advantages and limitations of various modeling tools can be found in the literature. For example, the accuracy of modeling hygroscopic materials has been discussed in detail by [12-16]. Collectively, these demonstrate that hygroscopic materials can be modeled, however the tools and required material properties may not be entirely representative, necessitating further investigation to ensure accuracy.

This study seeks to assess the hygrothermal performance and conduct a mold growth assessment of a building constructed using a CLT and WFI hybrid system. The building has been monitored over a 2-year period, with sensors installed in both the roof and wall assemblies. Hygrothermal simulations using WUFI Pro 7.0 have been validated using the measured data. This model was then used for calculating and evaluating the mold growth index of the assembly at multiple monitoring locations.

2 – PROJECT DESCRIPTION

The Cornerspring Montessori School Annex, Fig. 1, is a one-story CLT and WFI building, constructed in 2021 in Belfast, Maine, USA. The annex contains two classrooms in the 92 square meter footprint, which are occupied by 5-10 persons from September through June from 8:00 am to 4:00 pm on weekdays. Two mini-split heat pumps accompanied by an energy recovery ventilator condition the building. Wall and roof panels, consisting of 3- and 5-ply CLT and multiple layers of WFI board, were fabricated off site. As part of the prefabrication process, wall and roof panels at strategic locations within the building envelope were instrumented with temperature (°C), relative humidity (%), and moisture content (%) sensors. Readings were recorded for a two-year period. Resulting data was used to calibrate a one-dimensional hygrothermal model in the north- and south-orientation of wall envelopes. This was then used to assess the long-term durability and mold risk of the envelope.

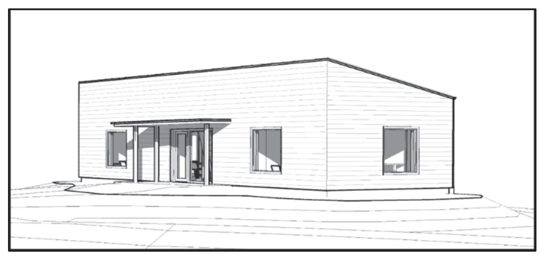

Figure 1. Rendering of the case study building, courtesy of OPAL Architecture

3 – EXPERIMENTAL SETUP

The Cornerspring Montessori School Annex was instrumented in summer of 2021, with reliable data being recorded starting in December of that year. Temperature, relative humidity, and moisture content sensors were installed at 13 locations throughout the building, Fig. 2. Locations were selected to assess conditions throughout the envelope, at building corners, and windows. For this analysis, the primary monitoring location in the North wall was selected. Note that primary monitoring positions are those that have temperature and relative humidity sensors at all layers within the envelope, and secondary locations only have sensors located at the innermost and outermost layers of WFI.

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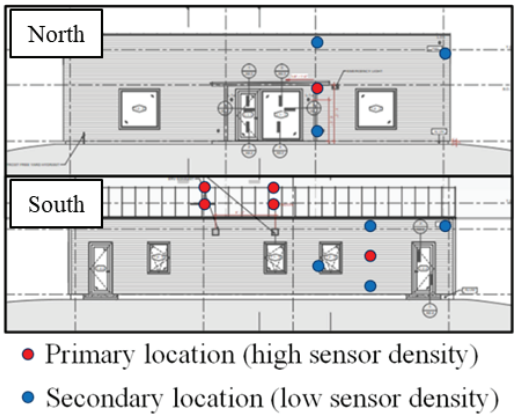

Figure 2. Monitoring locations throughout the building.

The selected monitoring location was instrumented with a moisture content sensor at the middle lamella of the CLT, and temperature and relative humidity sensors were installed between each layer of WFI. A number of moisture content sensors, including those at the selected monitoring position, were later found to be faulty. Replacement moisture content sensors have since been installed. Due to this being a functioning classroom, initial monitoring positions were not accessible and these new sensors were installed at convenient locations throughout the attic and where they would not be seen by occupants. Therefore, these are used for monitoring data, but are not included in this assessment. Sensor distribution and position naming scheme can be found in Fig. 3. As noted in this figure, positions will be referred to as P1, P2, and P3. P1 being the innermost position and P3 being the outermost position. A similar instrumentation and naming scheme was used for roof panels, which is also shown in Figure 3., however results for the roof are not included in this study.

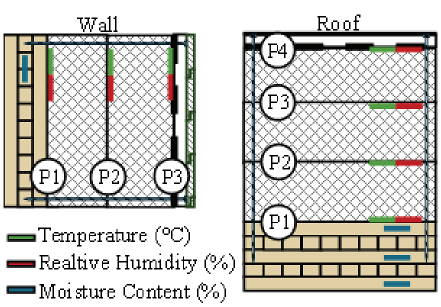

Figure 3. Distribution of temperature, relative humidity, and moisture content sensors through wall and roof assemblies at primary locations (high sensor density).

Measured data was collected over a 2-year period, starting Jan. 1, and then used as a baseline to validate the hygrothermal model. The results were compared using the root mean square error (Equation 1) and mean absolute error (Equation 2). Climate data was collected on site and supplemented with solar radiation values from the National Renewable Energy Laboratory (NREL) National Solar Radiation Database (NSRDB) [17]. The thermal properties of wood fiber insulation were measured and reported in Snow, *et al.* [18]. Other materials, including properties for CLT, were taken from the WUFI Fraunhofer material library and Glass, *et al.* [15].

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \hat{x}_i)^2}{N}} \qquad (1)$$

$$\text{MAE} = \frac{\sum_{i=1}^{N}|x_i - \hat{x}_i|}{N} \qquad (2)$$

The model was run for the 2-year period and compared to the measured data. Once there was agreement between the measured and simulated results, the model was run for a 5-year period using typical meteorological year (TMY) data and interior conditions meeting ASHRAE Standard 160-2021 requirements. This standard was also used for the mold growth assessment at each of the monitoring positions and the interior surfaces [19].

4 – RESULTS

Simulation results were assessed using the root mean square error and mean absolute error. A summary can be found in Table 1. Small discrepancies between MAE and RMSE indicate that large errors between monitored and simulated data are unlikely to occur.

Table 1. Summary of error between measured (M) and simulation (S).

Location	*Metric*	-	*Ave.*	*RMSE*	*MAE*
P1	Temperature (°C)	M	19.2	3.32	2.50
		S	21.6		
	Relative Humidity (%)	M	57.2	14.2	13.5
		S	43.7		
P2	Temperature (°C)	M	15.3	1.90	1.49
		S	16.1		
	Relative Humidity (%)	M	66.0	9.51	8.41
		S	58.3		
P3	Temperature (°C)	M	11.4	3.18	2.40
		S	10.5		
	Relative Humidity (%)	M	73.4	4.54	3.53
		S	74.0		

Further, error in RH increases from the outermost position (P3) to the innermost position (P1) of the WFI, Fig. 4, 5, and 6. This can be attributed to difficulty with modeling highly hygroscopic materials and thermal conductivity being measured at one environmental condition.

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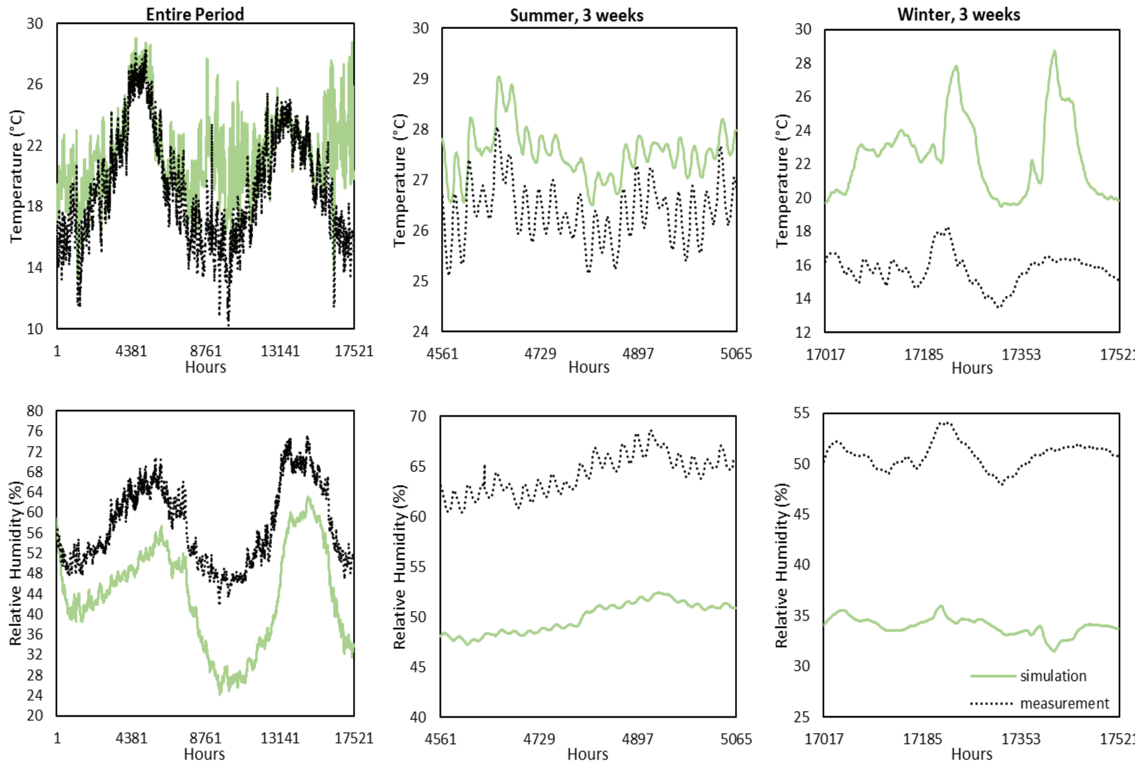

Figure 4. Measured and simulated temperature (top row) and relative humidity (bottom row) for North wall P1.

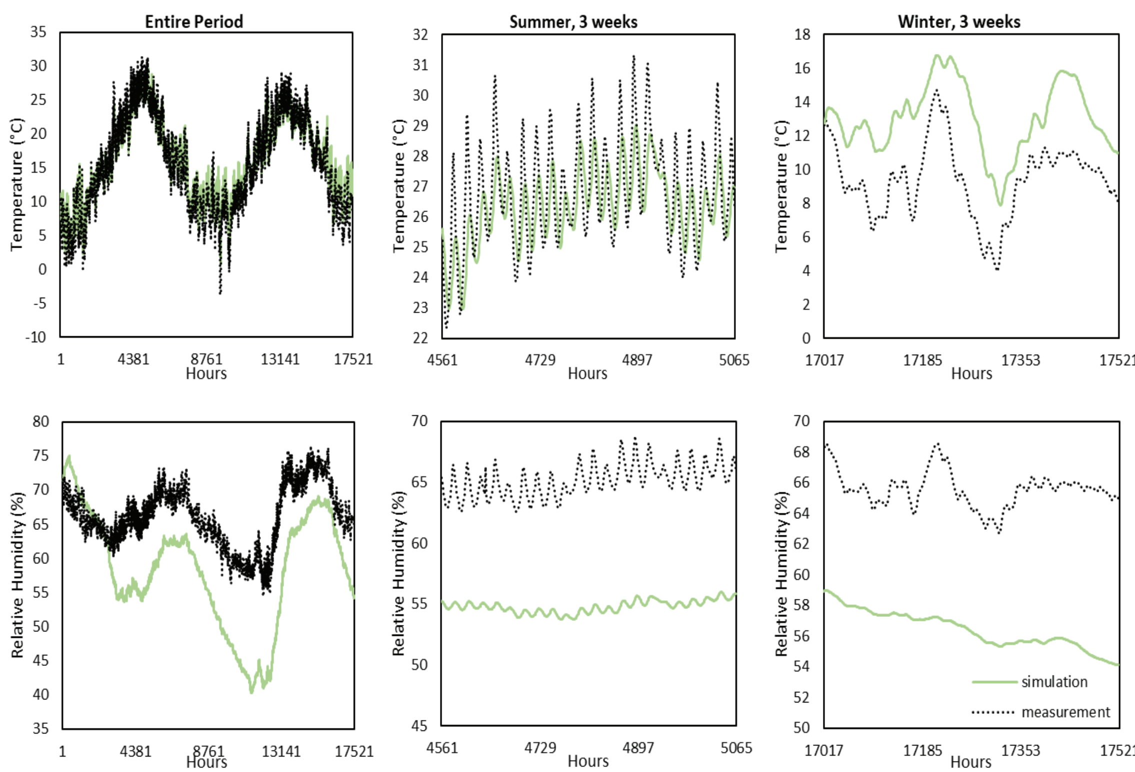

Figure 5. Measured and simulated temperature (top row) and relative humidity (bottom row) for North wall P2.

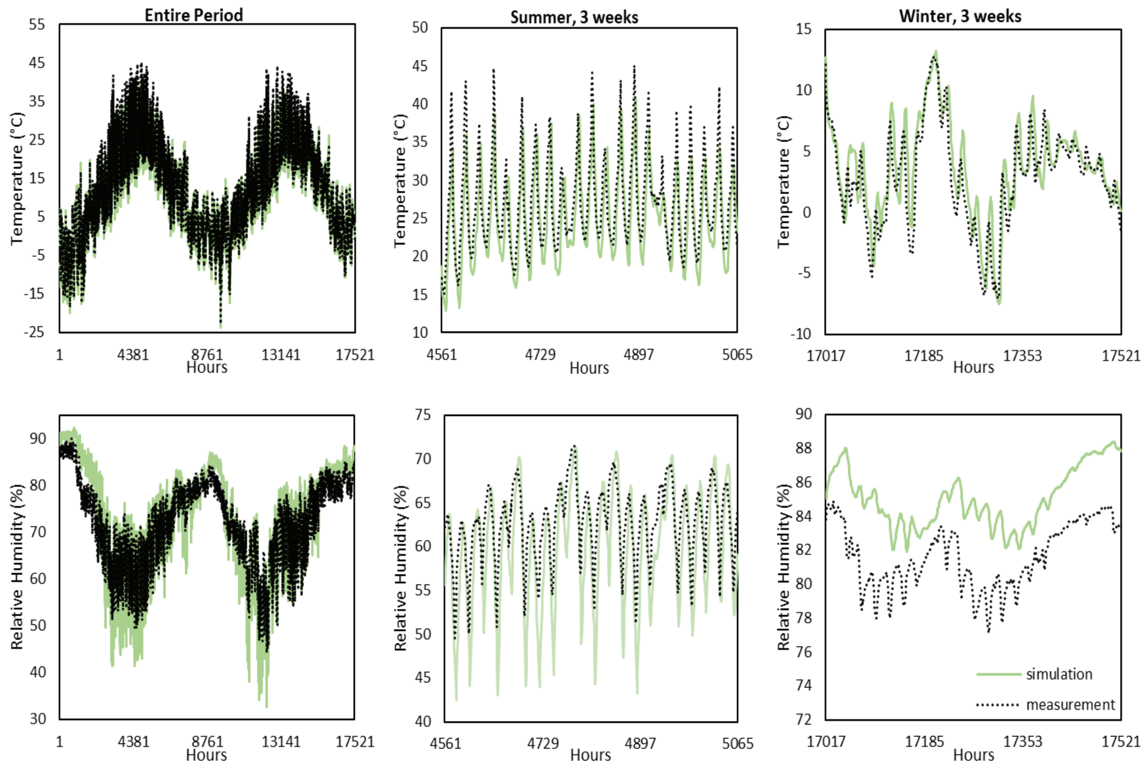

Figure 6. Measured and simulated temperature (top row) and relative humidity (bottom row) for North wall P3.

Simulated results at all locations follow general trends for temperature and relative humidity. This was plotted for a period of 3 weeks in July 2022 and December 2023 to better understand how the simulation is predicting hot and cold months. For temperature, the model is in good agreement with measured results, however there are greater discrepancies during the winter. Similarly, relative humidity follows general trends, which can be found in Figures 4, 5, and 6 for both summer and winter periods. However, the simulation is underpredicting relative humidity at a fairly constant magnitude at P1 and P2. Difficulty encapsulating moisture storage capacity and parallel moisture transport within the porous material and fibers is thought to be the cause of discrepancy.

A similar trend can be found in Bastien, *et al.*, who conducted field monitoring and hygrothermal simulation of a structure built with wood fiber insulation and clay [2]. They found that the material properties that are required by the WUFI software do not entirely represent hygroscopic materials and can lead to increasing error.

The ASHRAE 160 standard states that any location must not exceed a mold growth index of 3. The mold growth assessment found that there is no risk of mold growth at any of the monitoring locations. Results demonstrate that the greatest risk occurred during the first year at P3, which then decreased after initial drying. Results of the assessment, including maximum mold growth index and whether or not the monitoring position passed or failed according to the testing standard, are located in Table 2.

Table 2. Mold growth index results at all monitoring positions.

Location	***Maximum Mold Growth Index***	***Pass/Fail***
P1	0.075	Pass
P2	0	Pass
P3	0	Pass
Interior Surface	0	Pass

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5 – CONCLUSION

Agreement between the one-dimensional WUFI hygrothermal simulation and case study measurement was achieved. It was found that interior monitoring positions had greater error than exterior positions. This can be attributed to difficulties in simulating hygroscopic materials, and limitations with the measured properties of the materials. Further material characterization is required.

It was found that this CLT and WFI building system has not had any performance issues in US climate zone 6A, and modeling efforts demonstrated that there is currently no long-term risk of this system in this climate zone. Monitoring will continue to assess the performance of the building over a long-time horizon.

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