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VALIDATING MOISTURE-SAFE ENERGY EFFICIENT CLT ASSEMBLIES IN HOT AND HUMID CLIMATES USING EXPERIMENTAL TESTING

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ABSTRACT: Climate specific cross-laminated timber (CLT) construction detailing to manage moisture risks in subtropical and tropical regions of Australia is validated through experimental testing, statistical analysis, and computational hygrothermal modelling. Three projects in Australia are monitored: a CLT micro-unit built in a subtropical climate, a small CLT structure assembled inside a controlled double climatic chamber simulating a tropical environment, and an existing residential building located in a tropical climate. Several parameters are altered in the experiment design to understand the most reliable assemblies for CLT buildings in hot and humid climates that can sufficiently control the moisture risks. The findings suggest that the hygrothermal modelling guidance from ASHRAE 160 pertaining to construction unprotected from stormwater accurately represents CLT assemblies in hot and humid climates. The importance of adhering weather resistant membranes (WRB) to both the external face and edge grains of the CLT panels is revealed. In tropical climates, the positioning of internal insulation and WRB with increased vapour resistance are also shown to be beneficial, while ventilated cavities and drainage layers behind the cladding is critical for rain protection.

KEYWORDS: CLT, Hot and humid climates, Moisture, Construction wetting, Field monitoring, Energy efficiency.

1 INTRODUCTION

CLT construction and highly energy efficient buildings were originally developed and adopted in temperate and cold climates, where the vapour transfers predominantly from the inside to the outside. Instead, buildings in tropical and subtropical climates face different conditions, where cooling-dominated interior zones exert a vapour pressure in the direction of the interior for much of the year, due to high ambient relative humidity (RH) and temperatures. In addition, buildings constructed with CLT envelopes that are located in tropical climates have enhanced susceptibility to biotic deterioration [1] due to ambient temperatures and RH being within a range that is optimal for biotic growth to occur. As the market for energy efficient CLT buildings expands into these climates, performance testing and subsequent design adaptation is required. This is especially concerning in Australia, where the building industry has been slowly transitioning towards energy efficient buildings with increased levels of airtightness and thermal protection, adopting modern construction materials and practices that may exacerbate moisture risks. [2]. Therefore, this study focuses on experimental testing — including design and results — to validate simulation results and, thus, the proposed moisture safe solutions in subtropical and tropical regions.

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2 METHODOLOGY

Three projects in Australia were subjected to a monitoring campaign aimed to validate results of previous hygrothermal simulation. A CLT micro-unit has been designed and built at the Salisbury research facility of Queensland Department of Agriculture and Fisheries (DAF) and exposed to the hot and humid subtropical climate of Brisbane, as shown in Figure 1. A small CLT structure, employing the same assemblies of the micro-unit, has been placed inside a controlled double climatic chamber to simulate exposure to a tropical environment, as shown in Figure 2. Lastly, an existing CLT residential building located in tropical Cairns was also instrumented, as shown in Figure 3.

Figure 1: *The CLT micro-unit's shown before cladding is installed (left) and after installation (right)*

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Figure 2: The arrangement of the internal and external insulation of the small structure within the double climatic chambers is shown before the seal is completed between the two climatic chambers

Figure 3: Construction of a CLT residential project in Cairns, depicting the steel framing and ground floor CLT panels with scaffolding and the weather resistant membrane visible

The monitoring campaign of the three projects included the installation of moisture content (MC) sensors within the CLT panels. This was done to demonstrate the impact of different parameters and investigate the moisture performance and hygroscopic characteristics of the CLT structures over two phases. The first phase of the study monitored changes in MC of CLT panels through exposure to hot and humid climates during the 'construction' period, while the second phase investigated the change in vapour flow through the CLT assemblies once construction was complete and the building space was conditioned. The experiments allow the evaluation of specific parameters, including the influence of weather resistant membranes (WRB), location of the insulation layer (internal/external), and exposure of unprotected walls to high humidity and high temperature during construction, to verify moisture-safe assemblies developed in earlier studies using hygrothermal simulation for these same hot and humid climates [3]. The different parameters investigated in this study are shown in Figure 4.

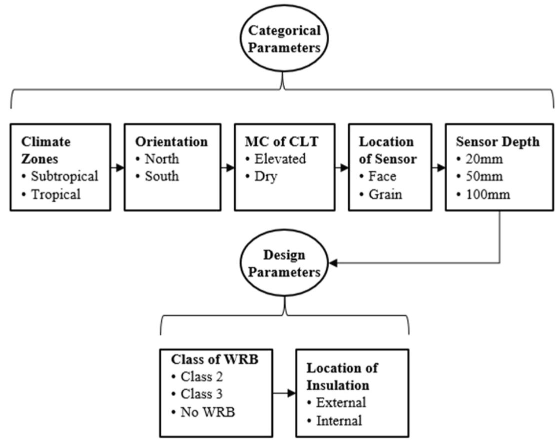

Figure 4: Parameters evaluated within the two experimental tests

The MC measurements were processed and inputted into calibrated hygrothermal simulation models to evaluate these parameters over the construction and operational phases. This was done to support the identification of the most appropriate CLT assemblies for hot and humid climates to avoid moisture risks.

2.1 CONSTRUCTION OF THE CLT MONITORING PROJECTS

The purpose of the three experiments was to cover specific climatic conditions for assessing long-term construction risks for CLT assemblies in hot and humid Australian climate.

2.1.1 CLT MICRO-UNIT EXPERIMENT

The CLT micro-unit was constructed to understand the impact of membrane vapour permeability on MC of the CLT panels during construction. For this reason, the two types of WRBs (a Class 2 and Class 3 product) were adhered to the external surface of the CLT panel on the north and south orientations. To assess the worst-case orientations, due to solar-driven inward diffusion effect on the north orientation and wind-driven rain and minimal drying potential effect on the south orientation. While the east and west oriented CLT panels were left exposed as reference cases. The CLT envelope was left exposed for 6 months during Brisbane's hot and humid summer season, as shown in Figure 5. This was expected to provide conservative results in terms of moisture risk, as a typical summer season in Brisbane was associated with the highest precipitation and RH for the year, which was a key consideration for this research. The duration of the experiment was decided to reflect worse-case delays during the construction phase of large-scale CLT buildings, for instance, due to procurement issues of the windows, concrete structure, or steel framing.

Figure 5: *The CLT micro-unit during the 'construction' period. The location of the sensor arrays on the interior CLT surface, the 2 WRB types, as well as the exposed CLT surfaces, edge grains, and rough door opening are visible*

The protected 'operational' phase commenced with the installation of the door, insulation panels, eave over the door, wall cladding, and roofing sheets flashed for rainfall drainage. A small, decentralised ventilation system with heat recovery and a small split system were also installed internally and activated during the 'operational' phase.

2.1.2 CLIMATIC CHAMBER EXPERIMENT

The climatic chamber experiment was developed to understand how CLT assemblies dry-out in tropical climates after construction wetting. This was done by changing certain parameters in the assembly, including the insulation layer location, vapour permeability of the WRB, and initial MC of the CLT panels. The configuration of the internal and external insulation, as well as the 2 types of WRBs with different vapour permeabilities can be seen in Figure 6.

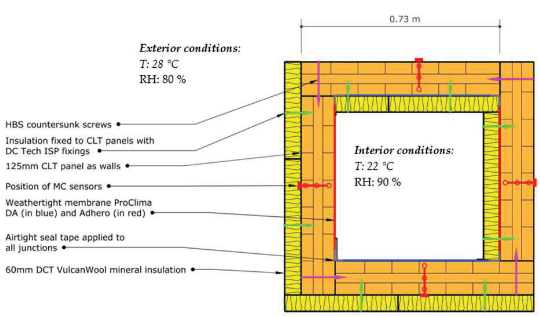

Figure 6: *The position of the insulation, different WRB types, and MC sensors in the double climatic chamber experiment*

To assess the influence of the initial MC of the CLT, 4 CLT panels were installed 'dry', while 4 CLT panels were 'wetted', letting them soak with a 10 mm layer of water sitting on their surface to represent two wetting events on-site, of 4 days and 7 days respectively, with a 10-day gap. All 8 CLT panels were then assembled in the double climatic chamber, as shown in Figure 7. The CLT assemblies were then subjected to 'exterior' condition of 28 °C and RH of 80 % for two months — a typical monsoon season in Cairns or Darwin. Insulation was then added, and the 'interior' condition was set to 22 °C and RH of 90 % for an additional two months, to represent an actively cooled building with a very high internal humidity loads, such as a kitchen or bathroom zone with an inadequate ventilation strategy.

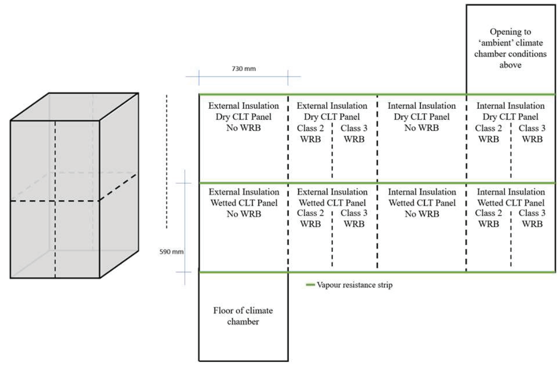

Figure 7: *Unfolded configuration of the CLT panels installed in the double climatic chamber*

2.1.3 RESIDENTIAL CLT BUILDING

A detached three-bedroom residential CLT building located in Cairns, comprising 180 m^2 of conditioned space was monitored over its construction period. No monitoring during occupation of the building took place. The project was instrumented to understand the moisture risks inherent with 'real-world' CLT buildings construction and the challenges of building with CLT in locations exposed to monsoon weather patterns. Only the north and south orientations were instrumented with MC sensors, as shown in Figure 8. As these were the worst-case orientations, due to solar-driven inward diffusion effect on the north orientation and wind-driven rain and minimal drying potential effect on the south orientation.

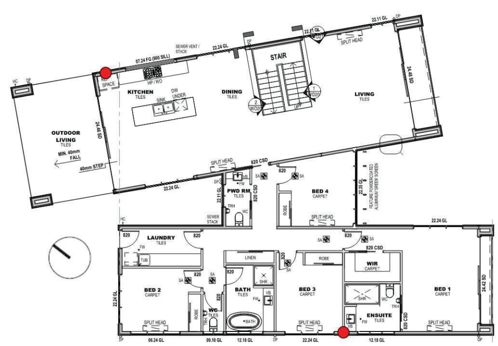

Figure 8: *Each red dots depicts the locations of two MC sensor arrays for the tropical residential construction (plan view)*

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2.2 INSTALLATION OF THE WIRELESS SENSING SYSTEM

The monitoring of the MC within all three projects was achieved with small, wireless, pin-type electric resistance moisture meters from OmniSense LLC (sensor S-11) [4]. The sensors have a sampling frequency of 6 minutes, a temperature error of ±2 °C, and a RH error of ±5 %. Installation of the MC sensors involved covering the MC probes (18-8 stainless steel mounting screws) with heat-shrink tubing to electrically isolate the screw shaft, while the screw head and tip were left exposed by 20 mm, to enable an electrical connection through the timber back to the electric circuit, and then embedded into the CLT panels as shown in Figure 17. The insulated probes were installed as arrays at three depths — 20 mm from the internal CLT panel surface, at the centre of the panel (50 mm from the internal surface), and 20 mm from the external panel surface (100 mm from the internal surface). An array of sensors was installed for each unique combination of assembly design parameters in each experiment, leading to the installation of 45 sensors in the CLT micro unit, 48 sensors in the double climatic chamber, and 18 sensors in the residential CLT project.

Figure 9: *A MC sensor with heat-shrink tubing and 20 mm exposed screw tip (left), then embedded in to the CLT wall (right) in the residential CLT building in Cairns*

2.3 CALIBRATION AND VALIDATION OF HYGROTHERMAL SIMULATIONS

Calibrated hygrothermal simulations require that the initial and boundary conditions represent the real conditions of the experiment as closely as possible. The monitored data of the external and internal boundary conditions, and the initial MC within the CLT panels were used for this purpose. The hygrothermal material properties were assigned from the material library within WUFI, which is the hygrothermal simulation tool utilised within this study. The dataset from the WUFI material library contains all the relevant hygrothermal properties to allow realistic simulation of the assembly layers used in the experiments.

2.3.1 BOUNDARY CONDITIONS FOR CALIBRATION

In the case of the CLT micro-unit and residential CLT building, the exterior boundary conditions were downloaded from a local weather station. While the exterior boundary conditions of the climatic chamber experiment and the interior boundary conditions for all three experiments were generated by RH and temperature sensors located in the plastic housing of the MC sensors. The temperature and RH values for the interior and exterior boundary conditions were processed and then formatted for use in WUFI. The boundary conditions are shown in Figure 10, Figure 11, and Figure 12 for the CLT micro-unit, double climatic chamber, and residential building, respectively.

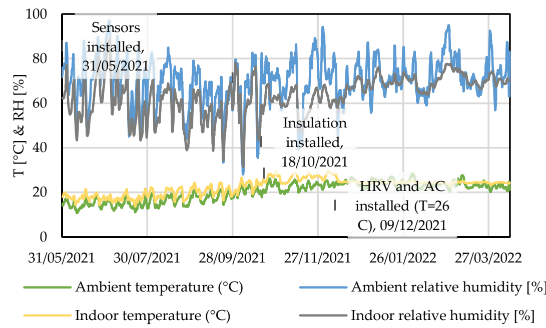

Figure 10: *The internal and ambient conditions from the naturally exposed prototype CLT micro-unit experiment in Salisbury. Data presented in a 24-hour moving average for visual clarity*

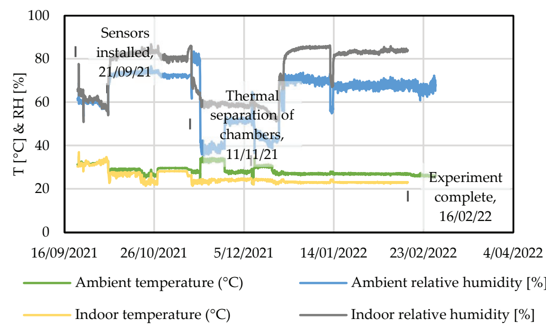

Figure 11: *The internal and ambient conditions from the double climatic chamber experiment simulating tropical conditions*

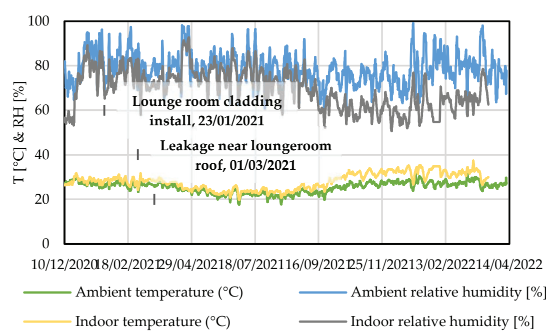

Figure 12: *The internal and ambient conditions from the tropical CLT residential building in Cairns. Data presented in a 24-hour moving average for visual clarity*

For the CLT micro-unit experiment, the air change rate in the 35 mm ventilated air gap behind the cladding was tested using an Almemo 2690 Ahlborn hand-held anemometer device [5]. Recordings were taken multiples times per day, over the course of two days, and the average air change rate was calculated as 54 ac/h. This appears to be a reasonable air change rate for fully ventilated fibre cement cladding, as air change rates of around 50 ac/h have previously been suggested in the literature [6], [7]. This air change rate was used as a boundary condition in both the hygrothermal models representing the CLT micro-unit and CLT residential building.

The initial MC settings used in the calibrated simulations were approximated by taking the average MC from the first 5 hours of MC monitoring for each sensor. This initial MC from each sensor was converted to a water content and assigned across the thickness of the three lamellae respectively. An example of the initial MC assignments can be seen for the CLT micro-unit, where Figure 13 depicts the 'construction' phase and Figure 14 depicts the 'operational' phase. These figures depict the 125 mm thick CLT panels which consist of 3 lamellae of radiata pine adhered together. Where in contrast to European CLT, it should also be noted that the edge gap of Australian CLT is not adhered.

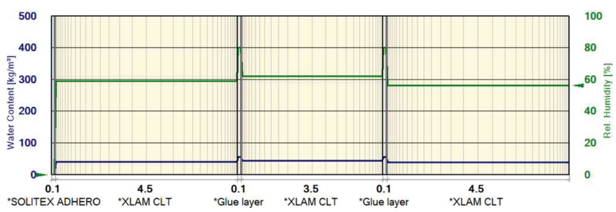

Figure 13: *Screenshot taken from WUFI of the cross-section of the CLT micro-unit wall assembly [cm] representing the 'construction' phase, where the initial MC assigned to the three lamellae is calibrated from the monitored data*

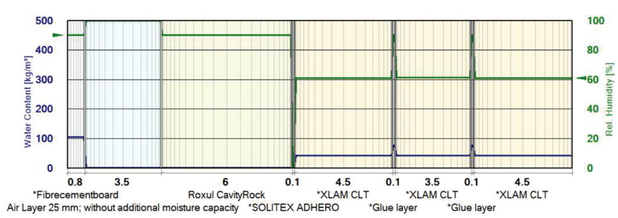

Figure 14: *Screenshot taken from WUFI of the cross-section of the CLT micro-unit wall assembly [cm] representing the 'operation' phase, where the initial MC assigned to the three lamellae are set to be consistent with the MC from the end of the 'construction' phase simulation.*

2.3.2 VALIDATION OF THE CALIBRATED HYGROTHERMAL SIMULATIONS

To validate the calibrated simulation data, hourly MC values were extracted from a 1 mm slice of CLT at the 20 mm, 50 mm, and 100 mm depths from the internal surface of the CLT panel to represent the positions of the MC sensors. The MC data from the sensors was cleaned by removing any null values and values lower than 8 % MC, which represented a loss of connection of the sensor probe with timber. Linear regression statistics packages were utilised in the statistical software R-studio and R to establish if a significant correlation exists between the simulated MC data and the monitored data. This was done by fitting the data to a regression model. The root mean squared error (RMSE) was used to quantify an error of deviation in the predictive quality from the simulations, as shown in Equation 1. While, the Pearson's product-moment correlation method was used to verify if sufficient correlation exists between the calibrated WUFI simulations and the monitored MC readings, as shown in Equation 2.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - f(x_i)\right)^2}$$

Equation 1: *Root mean squared error (RMSE) to measure average residual MC error [8]*

$$r = \frac{\sum(x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x}) \cdot (y_i - \bar{y})}}$$

Equation 2: *Pearson's correlation coefficient (r) [9]. Where 0 is equivalent to no relationship and 1.0 is equivalent to a perfect relationship*

If RMSE values were computed to be less than the average error of the OmniSense sensors, then the hygrothermal simulation was deemed to be validated. The variable error of a OmniSense sensor can be calculated by comparing the MC of radiata pine samples using the OmniSense sensors against the oven-drying gravimetric method. The variable error range of the OmniSense sensors can be defined by the equation given in Figure 15, and was thus used for the purpose of validating the WUFI simulations.

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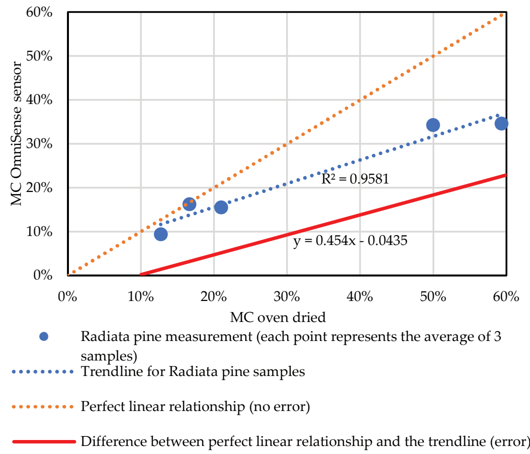

Figure 15: *Variable MC measurement error given for OmniSense sensors [10]. The coefficient of determination (R^2) is shown for the radiata pine samples, while an equation is given for the variable error*

3 RESULTS AND FINDINGS

Results from the monitoring campaigns of the three CLT projects in representative Australian subtropical and tropical climates are used to support notable observations about the monitored data relating to moisture risks within the CLT assemblies.

3.1.1 MONITORING OF THE CLT MICRO-UNIT

The monitoring data from some of the sensors in the CLT micro-unit shows that the sensor embedded in the assembly without a WRB has consistently higher MC, as shown in Figure 16; a maximum of 21.7 %, compared to the assembly with a WRB that records a maximum MC of only 13.1 %. MC of the assembly without a WRB remained higher even after the cladding was installed; showing that the assembly was never able to achieve a dry-out condition by returning to a MC equivalent to that of the assembly with a WRB over the monitored period.

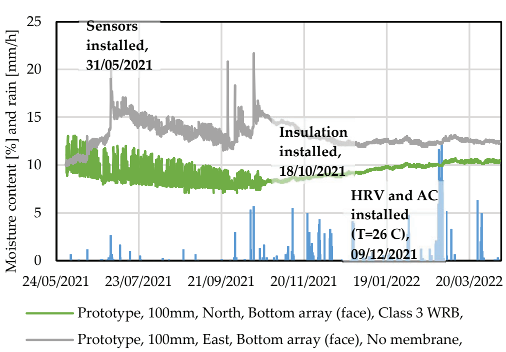

Figure 16: *Comparison between MC of an unprotected and protected CLT panel. Rainfall (mm/h) indicated by the blue vertical lines*

Table 1 statistically compares the CLT micro-unit predictive simulation results against the monitored results. The importance of installing a WRB can, again, been seen, as the assembly without a WRB had excessively high MC. It was also notable that Class 2 assemblies appeared to perform more poorly than Class 3. This was likely because the Class 2 WRB was not a pressure-adhered product; instead, it was stapled to the exterior surface of the CLT and then the staples were sealed with proprietary tape. It was noted that on windy days, air convection passed the Class 2 WRB, as movement of the membrane could be seen. This confirms the importance of using an adhered WRB product to avoid MC peaks during construction wetting. It should also be noted that the calibrated simulations for all assemblies returned maximum mould growth index (MGI) values that did not exceed the critical threshold of 3, which is given by ASHRAE 160 [11]. This means that, although peaks in MC may have occurred during construction, the long-term moisture safety was still ensured in subtropical climates.

Table 1: *D = embedment depth of sensor (mm). O = orientation of assembly. C = class of WRB. MC = maximum monitored MC (%), values greater than 18 % are highlighted in pink to indicate excessive moisture. R = RMSE (%), values highlighted in pink where the value exceeds the arithmetic mean sensor error. E = arithmetic mean sensor error (%). P = Pearson's correlation coefficient, values lower than 0.3 are highlighted in pink to indicate a weak relationship. MGI = maximum simulated MGI for the assembly*

D	O	C	MC	R	E	P	MGI
20	N	3	13.5	0.93	0.33	0.709	0.0161
50	N	3	12.4	0.52	0.55	0.446	
100	N	3	13.1	1.88	0.38	0.553	
20	N	2	16.5	0.60	0.74	0.713	0.0164
50	N	2	13.1	0.67	0.75	0.149	
100	N	2	13.5	3.20	0.56	0.444	
20	E	-	20.5	0.89	0.46	0.472	0.0654
50	E	-	24.2	1.41	1.23	0.608	
100	E	-	21.7	1.53	1.61	0.588	
20	S	3	13.9	0.45	0.67	0.821	0.0164
50	S	3	12.0	0.58	0.62	0.763	
100	S	3	10.4	1.24	0.12	0.713	
20	S	2	13.1	0.62	0.43	0.821	0.0163
50	S	2	21.6	1.79	0.90	0.066	
100	S	2	23.3	1.12	0.41	0.713	

3.1.2 MONITORING OF THE CLIMATIC CHAMBER

The monitoring data from the sensors in the double climatic chamber experiment shows that positioning vapour-open insulation internally is beneficial in maintaining a lower MC in comparison to externally positioned insulation (see Figure 17), departing from the construction method in cold and temperate climates with external insulation. However, Figure 18 demonstrates the importance of avoiding construction wetting for long-term moisture durability, for both external and internal insulation assemblies. As when wetted, the assemblies do not achieve dry-out equilibrium and continue to increase in MC over the duration of the experiment.

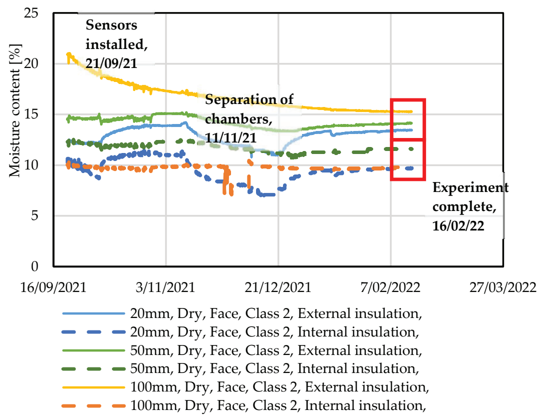

Figure 17: *Red rectangles highlight a comparison between the insulation position, external and internal*

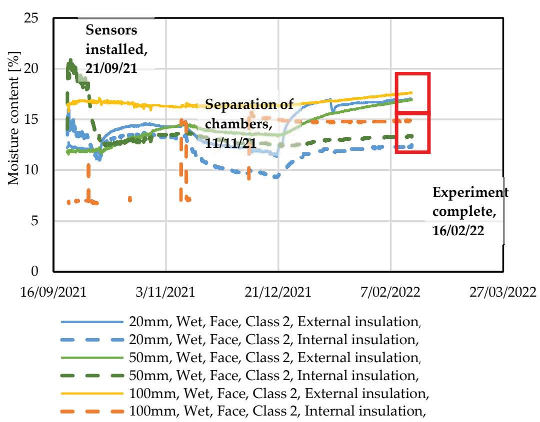

Figure 18: *Red rectangles highlight a comparison between the effect of construction wetting in tropical climate (dry and wetted panels)*

Table 2 summarise the CLT micro-unit monitoring results. It reveals that for dry assemblies, Class 3 WRB was most appropriate for assemblies with external insulation, while a Class 2 WRB was most appropriate for internal insulation. This is because a Class 2 WRB resists vapour from diffusing into the assembly. However, if the CLT panel is wetted, then the Class 3 WRB was most suitable to allow sufficient drying-out capacity. Predictive simulations were statistically compared against a few of the monitored results; this was because the 'ambient' boundary conditions of the climatic chamber experiment could not be correctly defined, as the air in the chamber was inadequately mixed. However, the MGI values for these assemblies did not indicate any mould growth over the duration of the experiment.

Table 2: *D = embedment depth of sensor (mm). L = location of insulation, external (e) or internal (i). C = class of WRB. I = initial state of CLT, wetted (w) or dry (d). MC = maximum monitored MC (%), values greater than 18 % are highlighted in pink to indicate excessive moisture. R = RMSE (%), values highlighted in pink where the value exceeds the arithmetic mean sensor error. E = arithmetic mean sensor error (%). P = Pearson's correlation coefficient, values lower than 0.3 are highlighted in pink to indicate a weak relationship. MGI = maximum simulated MGI for the assembly*

D	L	C	I	MC	R	E	P	MGI
20	d	3	e	12.3	1.75	0.67	0.957	
50	d	3	e	12.4	0.56	1.03	0.168	0.1116
100	d	3	e	11.4	1.21	0.37	0.721	
20	d	2	e	14.2				
50	d	2	e	15.2			-	
100	d	2	e	21.0				
20	d	-	e	19.9	2.03	1.72	0.759	
50	d	-	e	14.4	1.07	1.32	0.532	0.0660
100	d	-	e	15.7	1.53	1.20	0.477	
20	w	3	e	18.4				
50	w	3	e	17.9			-	
100	w	3	e	21.6				
20	w	2	e	17.1				
50	w	2	e	16.9			-	
100	w	2	e	17.6				
20	w	-	e	27.8				
50	w	-	e	21.7			-	
100	w	-	e	26.9				
20	d	3	i	13.4				
50	d	3	i	13.8			-	
100	d	3	i	17.1				
20	d	2	i	11.4	2.44	0.41	0.910	
50	d	2	i	12.5	0.53	0.97	0.205	0.0893
100	d	2	i	10.5	1.05	0.15	0.045	
20	d	-	i	14.0			-	
50	d	-	i	13.7				

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100	d	-	i	13.7	
20	w	3	i	15.2	
50	w	3	i	17.1	-
100	w	3	i	17.8	
20	w	2	i	16.0	
50	w	2	i	20.9	-
100	w	2	i	15.9	
20	w	-	i	15.1	
50	w	-	i	14.6	-
100	w	-	i	14.4	

3.1.3 MONITORING OF THE RESIDENTIAL CLT BUILDING

The monitoring data from the sensors in the CLT residential building shows the moisture risks due to leaks in roof cladding over the north-east wall orientation, causing high MC. Figure 19 shows a MC range of 17.5–28.2 % for a sensor in the north-east orientation, compared to the equivalent sensor in the south-west assembly that was not exposed to the roof leak, with a lower MC range of 8.7–17.8 %.Table 3 statistically compares the CLT micro-unit predictive simulation results against the monitored results. This shows a general trend for sensors installed near the CLT floor panel, which had a greater predisposition for higher MC ranges. This was likely due to the window frame rough openings during construction, which allowed stormwater to pass inside of the construction and be absorbed into the CLT floor panel end-grain. However, the MGI values for these assemblies were shown to be less than the critical threshold over the duration of the experiment.

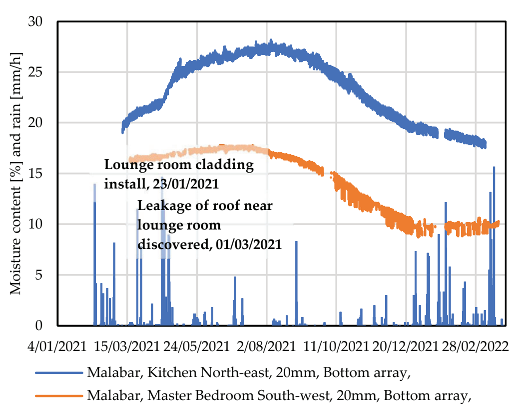

Figure 19: *Comparison between the effects of a roof leak. Rainfall (mm/h) indicated by the blue vertical lines*

Table 3: *D = embedment depth of sensor (mm). O = orientation of assembly. C = class of WRB. L = location of array, upper (u) or lower (l). MC = maximum monitored MC (%), values greater than 18 % are highlighted in pink to indicate excessive moisture. R = RMSE (%), values highlighted in pink where the value exceeds the arithmetic mean sensor error. E = arithmetic mean sensor error (%). P = Pearson's correlation coefficient, values lower than 0.3 are highlighted in pink to indicate a weak relationship. MGI = maximum simulated MGI for the assembly*

D	O	C	L	MC	R	E	P	MGI
20	NE	3	l	28.2	8.14	6.35	0.235	
50	NE	3	l	26.5	2.4	4.30	0.765	0.7159
100	NE	3	l	19.0	1.98	3.38	0.564	
20	NE	3	u	14.8	2.63	0.60	0.798	
50	NE	3	u	18.8	2.14	3.10	0.838	0.1635
100	NE	3	u	21.4	2.39	2.57	0.791	
20	SW	3	l	17.8				
50	SW	3	l	17.0			-	
100	SW	3	l	17.5				
20	SW	3	u	13.8	2.55	1.19	0.787	
50	SW	3	u	13.6	1.54	1.12	0.476	0.1229
100	SW	3	u	12.8	3.31	0.65	0.628	

3.1.4 LIMITATIONS OF THE STATISTICAL RESULTS FOR THE CALIBRATED MODELS

Generally, the statistical results of the monitored data and calibrated simulations indicate a strong measure of closeness from the Pearson's correlation coefficients. However, the RMSE values are generally larger than the mean sensor error, which means that calibration is not validated for the respective sensor. Only 30 % of the calibrated simulations achieved both the accepted values for Pearson's correlation and RMSE values, and thus can be deemed validated. While this shows that calibration is possible, it also shows that more accurate knowledge of boundary conditions and a higher quality representation of the microclimate may align the other simulations with the monitored data. A notable observation was that the sensors embedded closest to the external surface had the worst correlation to the measured MC values. Therefore, the weather data collected at nearby weather stations may insufficiently represent the 'microclimate' around the projects for adequate calibration.

In the case of the CLT residential building, failure to sufficiently calibrate the models was due to leaks occurring during the construction phase. This was because the exact nature of the stormwater's flow, speed, and path could not be adequately represented by a simple ratio of driving rain applied to a position within the assembly. However, this failure to calibration for leaks was also interesting because they appear to validate guidance from ASHRAE 160, which recommends assigning an initial MC of two times the equilibrium MC at a RH of 80 % across the entire assembly when construction sites were not protected from stormwater. Following this guidance would have led to an initial MC of 30 %, which accurately represents the peak MC due to the leak. This suggests that for projects where defects such as water intrusion past the roofing may occur during construction (practically all projects), this 'unprotected' modelling guidance should be used to assess long-term moisture risks. Additionally, this guidance avoids overly complex procedures, such as 3D hygrothermal modelling or quantifying the exact amount of water leaking through an envelope defect. However, it should be noted that this same modelling approach is not capable of replicating the exact nature of the stormwater's flow and thus, it cannot be used to calibrate simulations.

Calibration of the hygrothermal simulations for the climatic chamber experiment was also problematic because the sources of heating, cooling, and humidification were all localised on one side of the chamber, with insufficient blending of the air volume, which led to non-homogenous conditions within the climatic chambers. To resolve this issue in future experiments, internal fans or diffusers should be installed in each chamber to distribute and disperse the conditioned air evenly around the monitored space.

4 CONCLUSIONS

Results from the monitoring campaigns of three CLT construction projects are used to draw conclusions about moisture risks in hot and humid Australian climates.

A notable observation about the monitored data relating to moisture risks within the CLT assemblies is that, in hot and humid climates, external insulation is appropriate — which is supported by simulation results. However, in tropical climates, positioning of insulation on the internal CLT face, and airtight and vapour resistant membranes positioned behind the cladding are shown to be beneficial. Good interior ventilation strategies as well as ventilated cavities and drainage layers behind the cladding are also highly advantageous for improved moisture safety. These results also show that adhered WRBs are critical for moisture safety.

The simulations revealed a faster drying sequence in the monitored data as compared to WUFI simulations. In addition, regardless of the difficulty in calibrating the hygrothermal simulations with the monitored data, the simulations showed a low MGI, and thus moisture safety in the CLT assemblies. This corresponded with the monitored data, which showed that despite elevated MC during the 'construction' stage, the MC dropped to safe levels during the 'operational' stage. The simulation results also confirm that the guidance about simulation settings and initial conditions given by hygrothermal standard ASHRAE 160 are appropriate for CLT assemblies in hot and humid climates.

Future work would use the simulated MGI values from the calibrated simulated MC values to produce a maximum initial MC to maintain moisture safety for the various CLT assemblies in hot and humid climates. Additional details and discussions about these monitoring campaigns can be found in the PhD thesis by the primary author.

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