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Hygrothermal Modeling and Laboratory Tests of Solar-Driven Moisture Diffusion in Wood-Frame Walls with Absorptive Claddings

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ABSTRACT

Transient conditions arising from sun exposure of absorptive claddings after being wetted by rain impose significant hygrothermal load on wood-frame walls. In this paper, we show that moisture conditions generated by the inward drive of water vapor increase the risk of mold growth and durability issues in susceptible components of the wall assembly. We present a comprehensive set of one-dimensional hygrothermal simulations on solar-driven moisture diffusion in wood-frame walls with brick cladding and oriented strand board (OSB) sheathing. Sensitivity analysis identifies key material transport properties with critical effect on moisture dynamics in wood-frame assemblies, such as the vapor permeance of the weather resistive barrier and ventilation of the air gap behind the brick cladding. Informed by the results of the simulations, full-scale test walls are designed, and their moisture performance evaluated in a one-of-a-kind analytical chamber, the CARWASh, equipped to generate controlled indoor and outdoor environments with realistic wind-driven rain and sun exposures. A grid of sensors monitors the relative humidity, temperature, and moisture content at different heights and depths of the wall assembly to capture critical spatial and temporal variations. These in-situ measurement results are intended to be compared with simulated values for validation. The results overall are intended to assist building designers in their efforts to minimize the risk of moisture accumulation in wall assemblies across different U.S. climates.

INTRODUCTION

Prior research has found that inward moisture diffusion from absorptive claddings such as brick veneer, stucco, or adhered stone veneer can be significant in wood-frame walls (Derome 2010; Smegal and Grin 2015; Derome and Saneinejad 2010; Carmeliet and Derome 2012). When the cladding is heated by the sun after being wetted by rain, the vapor pressure elevates, and the inward migration of moisture increases. The magnitude of the inward vapor drive depends on a number of climate factors, for example, the amount of wind-driven rain that hits the wall, whether the rain occurs significantly during the warmer months of the year, and how quickly solar irradiance increases after rain. Moisture driven through the vapor permeable water-resistive barrier (WRB) can accumulate within the wall if the interior side of the assembly is too low in permeance relative to the exterior side of the assembly. In wood-frame construction, this problem has been observed when low-permeance materials such as polyethylene or vinyl wall covering are used on the interior. The problem is intensified in air-conditioned buildings often resulting in condensation on the cool interior surfaces. Research has highlighted the importance of inward drying not being impeded (Derome and Saneinejad 2010).

Controlling inward vapor flow from absorptive claddings is difficult. Back ventilation of the cladding is generally recommended as the first defense. This is achieved by creating a cavity between the cladding and the rest of the assembly that is open to airflow. Brick veneer, for example, is typically installed with a drainage cavity and weep holes. Air exchange rates

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in brick veneer cavities are typically much smaller than in cavities that have larger openings at top and bottom, such as wood siding or cement board installed on furring strips (Burnett et al. 2004; Finch and Straube 2007). Back ventilation may not be a reliable strategy for brick veneer constructed using common practice, given the lower air exchange rates and the possibility of localized areas where mortar bridges the cavity. The second defensive measure involves the placement of a non-moisture-sensitive, low-permeance material between the cladding and the rest of the assembly. Claims that low permeability is needed in hot and humid climates and that WRBs with high permeability ratings are not suitable to sufficiently throttle back solar-driven vapor diffusion and prevent moisture accumulation are subjects of contention (Tyvek 2023). Although the phenomenon of solar-driven moisture diffusion is acknowledged and its negative influence on moisture-sensitive wall components has been demonstrated, field studies are still limited.

Hygrothermal simulation is an important alternative to model solar-driven vapor drive and moisture accumulation, but it may overpredict the need for vapor restriction and may unnecessarily suggest an exterior vapor barrier (VaproShield 2017). For the hygrothermal simulation to correctly predict the moisture performance of wood-frame walls with absorptive claddings, both accurate input parameters (Boardman and Glass 2020) and validated models are required. This may be accomplished with laboratory investigations that are representative, i.e., exposing the exterior boundary of the wall to real weather conditions. In most laboratory studies, however, inward moisture diffusion is commonly investigated from a hygrothermal prospective with boundary conditions that are not strictly aligned with realistic climate and/or in service loading (Carmeliet et al. 2007). To achieve an acceptable degree of accuracy, care is also needed in selecting the measurement sensors and instrumentation (Straube et al. 2002). Systematic monitoring of the relative humidity and moisture content at all locations that are prone to moisture damage is also essential for data interpretation. Inconsistent monitoring leads to more questions than answers. A field study of brick walls tested in Charleston, SC, for instance, may have overlooked the moisture risk at the exterior side of the wood sheathing because it correlated relative humidity levels at the outer side of the sheathing with moisture contents of the wood framing inside the cavity (Jablonka et al. 2010).

Our goal is to expose wood-frame walls with brick cladding and oriented strand board (OSB) sheathing to a full range of exterior boundary conditions in a laboratory test environment that closely mimics the rate, magnitude, and sequence of real weather events in a hot and humid climate. These well-controlled, yet realistic tests are expected to provide us with reference data for model validation and a pragmatic understanding that can then be extrapolated over longer timeframes and extended to other transient moisture conditions, different climates, or wall assemblies (Straube et al. 2002). Specifically, we identify key variables with critical effect on solar-driven moisture diffusion—such as the vapor permeance of the WRB and ventilation of the air gap behind the brick cladding—through a comprehensive set of one-dimensional hygrothermal modeling and sensitivity analysis. Informed by the results of the simulations, we design full-scale test walls and a synthetic weather pattern with realistic wind-driven rain and sun exposures for the assessment of moisture performance in a one-of-a-kind analytical chamber, the CARWASh.

METHODS

In this study, we employ a commonly used hygrothermal simulation program for building design—WUFI Pro software, version 6.7—which calculates transient coupled heat and moisture transport in wall assemblies. For the sensitivity analysis, we utilize the WUFI database and chose the 'cold year' weather and ASHRAE Standard 160 for Miami, FL as inputs for the exterior and interior boundary conditions, respectively. After identifying weather patterns yielding extreme solar-driven moisture diffusion over several weeks of a timeframe, we design an equivalent, synthetic weather for laboratory testing of wood-frame wall assemblies typical for low-rise residences. When making comparisons between experimental results and hygrothermal simulations, inputs for the boundary conditions will be the relative humidity and temperature values measured in the outdoor and indoor chambers of the CARWASh (Chamber for Analytical Research on Wall Assemblies exposed to Simulated weather) during testing.

The CARWASh is a special laboratory facility that generates true-to-size raindrops and uses the force of simulated wind to deliver water to the wall, which is significantly more realistic than spray tests that rely on large pressure differences to simulate rain intrusion. Details regarding the local distribution and quantification of wind-driven rain on exterior walls tested in the CARWASh under different wind speeds and rain intensities are reported by Boardman and Glass (2013). Vital to our investigation is the unique capability of the CARWASh to subject test walls to controlled wind-driven rain and solar exposures that are realistic of a hot and humid climate.

RESULTS AND DISCUSSION

Moisture Gradient in Oriented Strand Board Sheathing

Moisture diffusivity of wood-based building materials is very low; hence, large moisture gradients can readily develop in situations where high rates of drying or wetting occur on the surface (Straube et al. 2002). OSB consists of layers of wood strands partially separated by layers of adhesives, which further limits diffusion leading to even larger gradients. It has been acknowledged that moisture failures generally occur either at the interior sheathing surface because of interior-sourced interstitial condensation, or the exterior surface for rain penetration for instance (Lstiburek et al. 2016). In case of solar-driven moisture damage, the exterior surface of the OSB is expected to be more vulnerable than the interior surface. Nevertheless, some investigations have been limited to the moisture content of the interior surface of the OSB or wood framing inside the cavity (Lstiburek et al. 2016; Jablonka et al. 2010). Such an approach may underestimate the risk of moisture damage for typical south-facing wall assemblies with brick cladding and OSB sheathing in a hot and humid climate.

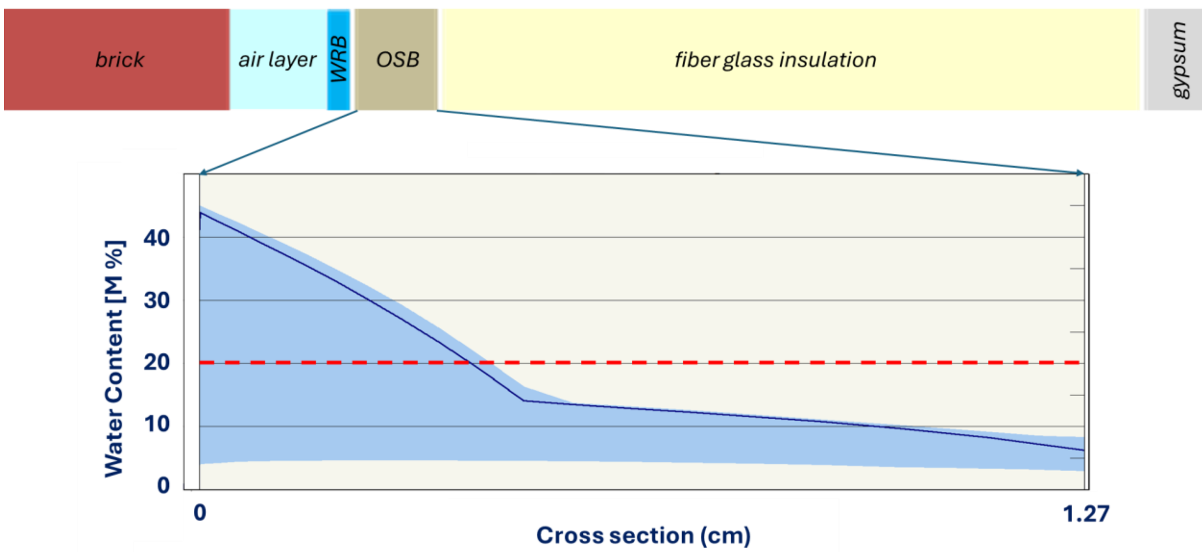

Figure 1 Range of moisture content values of OSB in a typical wall assembly with brick cladding in Miami, FL simulated over a period of 3 years. Left side: exterior, right side: interior. The dashed line marks the critical level for moisture risk. Light blue shaded area shows the range of values, while the dark solid lines are a representative moisture content profile. 1.27 cm equals ½”.

Figure 1 shows the range of moisture contents an OSB sheathing exhibits over a period of 3 years in a typical wall assembly with brick cladding in Miami, FL. The largest moisture gradient is about 5% mm^{-1} (5% per 0.04”); the largest moisture content at the exterior surface of the OSB is way above the critical 20% level. Figure 1 also shows that the elevated relative humidity conditions at the exterior side did not cause the moisture content in the interior half of the OSB to rise to critical levels. In laboratory studies under extreme environmental conditions, elevated relative humidity levels measured at the exterior surface of the OSB have been correlated with the presence of mold growth (Carmeliet and Derome 2012). For accurate assessment of mold growth risk, it is therefore prudent to capture not only the temporal but the spatial variations of the OSB moisture content, particularly when transient conditions arising from exposure to real weather are involved.

Sensitivity Analysis for Key Variables

Permeance of the WRB. One of the most influential components of the wall assembly to control inward transport of vapor is the permeance of the WRB. To inform the design of wall assemblies for laboratory testing, we model solar-driven moisture diffusion in wall assemblies with different WRB permeance ratings. Our evaluation criterion for the inward vapor drive is based on the results in Figure 1. We calculated the average moisture content of the exterior ⅛ inch-layer (3.2 mm) of the OSB over a period of 3 years and determine the peak moisture content as a function of permeance.

Figure 2 shows that the permeance of the WRB strongly affects how much the solar-driven moisture diffusion is throttled back, preventing high levels of moisture accumulation in the OSB sheathing. These results seemingly disagree with studies that show no significant difference in inward vapor drive based on WRB permeability (Tyvek 2023). The latter observations, however, were based on a very different evaluation criterion. In those studies moisture content on the exterior surface of the interior gypsum board was measured to assess inward vapor drive in terms of WRB permeability. We suppose that the indifference of the WRB's permeability reported in (Tyvek 2023) is due to the very low diffusivity of the OSB as discussed above. The OSB sheathing appears to be effectively protecting the interior side of the wall. On the other hand, the exterior surface of the OSB remains vulnerable to moisture damage, the level of which would depend on the permeance of the WRB and must be investigated.

Toward this, we will study the moisture performance of walls with a single layer of a conventional spunbonded polyolefin-based WRB, which allows the moisture content of the most exterior layer of the OSB to increase well above the critical 20% level (open triangle in Figure 2). In addition, we will construct walls with significantly higher vapor retarding characteristics by installing a thin layer of extruded polystyrene insulation on the exterior side of the spunbonded polyolefin-based WRB (open square in Figure 2).

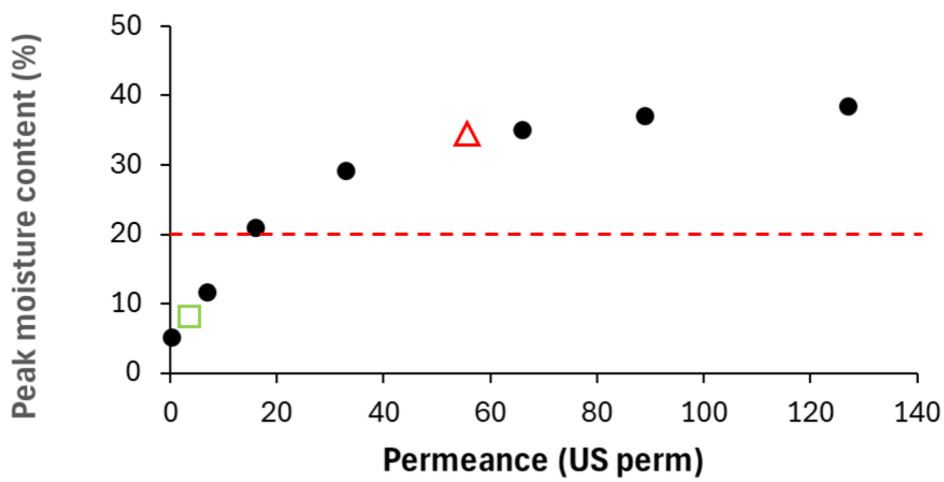

Figure 2 Peak moisture content of the exterior ⅛ inch-layer (3.2 mm) of the OSB over a period of 3 years in Miami, FL as a function of the permeance of the WRB. The open triangle and square represent examples of a highly permeable and a semi-permeable WRB option, respectively. The dashed line marks the critical level for moisture risk. 1 US perm equals 57 ng m^{-2} s^{-1} Pa^{-1}.

Cavity Ventilation. An air gap between the back side of the cladding and the drainage plane plays an important role in terms of providing an additional control layer against solar-driven moisture diffusion. While ventilation may not facilitate the drying out of the brick cladding significantly, it is expected to reduce the relative humidity levels within the cavity (Vanpachtenbeke et al. 2020). Implementation of cavity ventilation in hygrothermal simulations is not trivial. For one-dimensional simulations, the source/sink approach provides the least uncertain results (Vanpachtenbeke et al. 2020). For vented brick claddings, a value of 10 air changes per hour (ACH) is representative of a typical air change rate between the cavity and the outdoors (Lstiburek et al. 2016).

At this rate, we find the impact of ventilation on the moisture content at the exterior surface of the OSB insignificant. To eliminate some of the large uncertainties associated with both the measurement and simulation of air change rates, our wall design will allow testing with no ventilation. While this is not realistic or recommended, testing of the walls with no ventilation will provide us with laboratory data with different moisture dynamics facilitating our model validation efforts for solar-driven moisture diffusion.

Synthetic Weather Pattern for Laboratory Testing in the CARWASh

Our goal is to expose wood-frame walls with brick cladding and OSB sheathing to a full range of exterior boundary conditions in a laboratory test environment that closely mimics rate, magnitude, and sequence of weather events in a hot and humid climate. We chose Miami, FL as a representative location. Through hygrothermal simulations, we identify weather patterns that would yield significant solar-driven moisture diffusion over a month timeframe. The starting point is chosen just before a significant rain event, so that in 5 days the moisture content of the brick rises well above 100 kg/m^3 (6.24 lb/ft^3), which has been found significant (Carmeliet and Derome 2012). Under the selected weather pattern, the drying rate of the brick is relatively slow, and subsequent rain events are expected to keep the brick saturated or close to saturated preventing the moisture content at its interior surface to fall significantly (Shahreza 2022).

Next, we convert the selected weather pattern to equivalent exposure conditions for testing in the CARWASh. We estimate the vertical component of the radiation—which will be received by the test walls—by applying a scaling factor of about 1/3 to global horizontal radiation data from the National Solar Radiation Database. This scaling factor seems to be consistent on average with ratios of vertical and horizontal radiation that have been previously measured, although in a different climate (Glass 2015).

To see how well the synthetic weather mimics the selected real weather pattern, we compare the temperature, relative humidity and the moisture content of the brick across its thickness. Figure 3 shows that the agreement between the ranges and profiles of these values is very good, confirming that the synthetic weather closely reproduces the real weather in Miami, FL between May 17 and June 17.

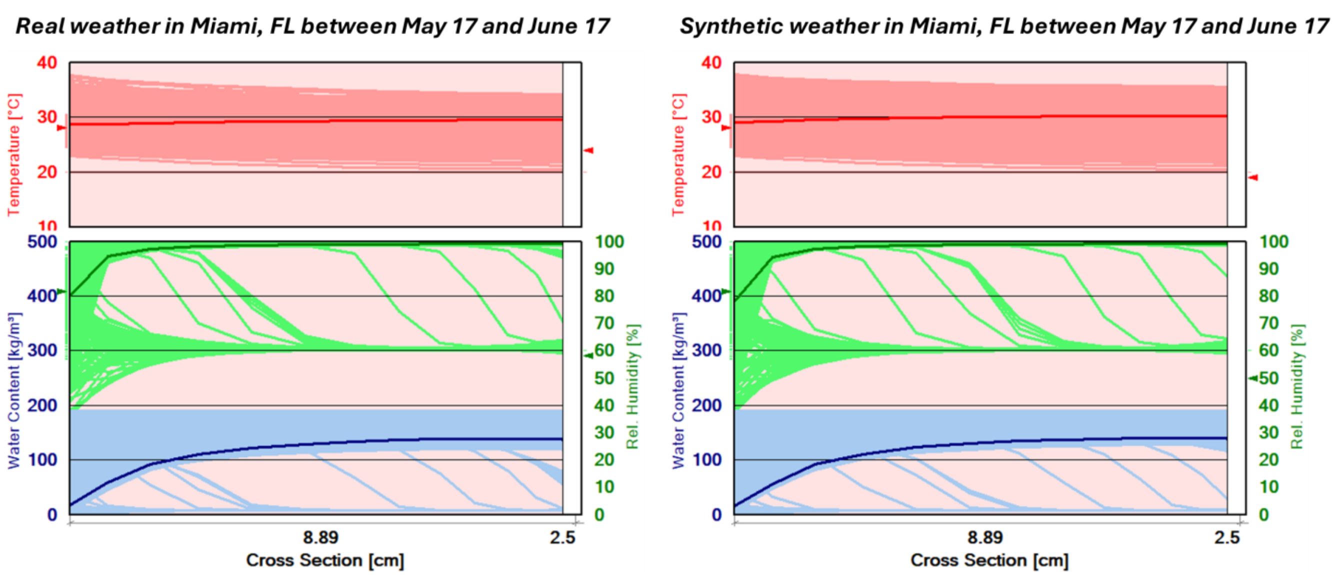

Figure 3 Comparisons of temperature, relative humidity and the moisture content of the brick across its thickness generated with real and corresponding synthetic weather data. Lighter colors show the range of values, while the dark solid lines are profiles obtained at the end of the weather pattern. 10–40 °C equals 50–104 °F; 0–500 kg/m^3 equals 0–31.2 lb/ft^3; 8.89 cm equals 3.5”.

Wall Design and Sensor Locations

Synthetic weather at hand, we turn our attention to finalizing the design of the full-scale test walls with goals of generating better understanding and experimental data for model validation of solar-driven moisture diffusion. Based on the results of the comprehensive set of hygrothermal simulations discussed thus far, we are constructing different wall assemblies to investigate the impact of WRB permeance and the presence of low-permeance materials on the interior side. Each test wall consists of an OSB sheathing, R21 fiber glass cavity insulation, and interior gypsum board. The exterior face of the wall is covered with a brick veneer installed with a 1” air gap (25.4 mm) between the back side of the cladding and the drainage plane, which is provided by a single layer of a conventional spunbonded polyolefin-based WRB. This basic wall structure is modified by the addition of different combinations of external insulation, interior polyethylene vapor barrier, and gypsum board finishes as shown in Figure 4. Additional iterations will investigate the effect of cavity ventilation.

Systematic monitoring of the relative humidity and moisture content at all locations that are prone to moisture damage—particularly at the exterior surface of the OSB sheathing—is essential for accurate data interpretation of solar-driven moisture diffusion. Accordingly, we will outfit each test wall with three pairs of moisture-pin probes—one centered at middle height of the wall, the other two centered at 6” (152.4 mm) from the top and bottom of the wall. Each pair/location consists of an uninsulated short pin—one installed from the exterior, the other from the interior. These sensors are to monitor the moisture content in the exterior and interior parts of the OSB. The moisture content sensors are accompanied by combined relative humidity and temperature probes at all locations. The moisture content of the OSB is calculated from the measured resistance and the associated temperature using the correlation developed by Boardman et al. (2017). The relative humidity and temperature are also measured at mid-depth of the ventilation cavity behind the brick wall, and between the fiber glass insulation and gypsum board at top, bottom, and center heights. An additional pair of moisture-pin probes is installed to record the moisture content of the wood baseplate at the bottom of each wall. A schematic of the sensor layout at the center height of the wall is shown in Figure 4.

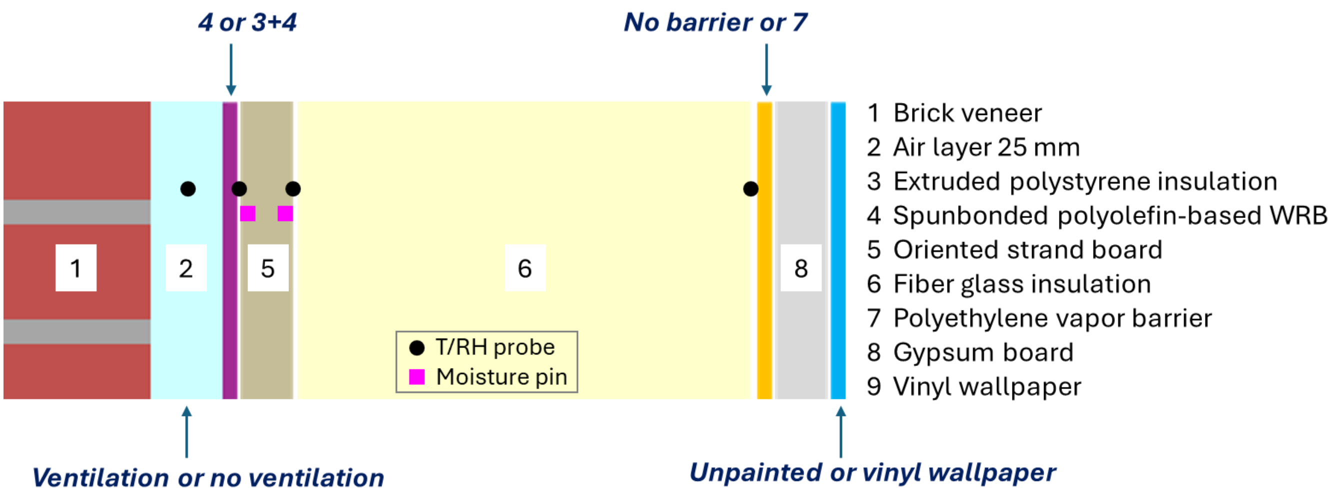

Figure 4 Design and sensor layout for laboratory testing of full-scale, wood-frame wall assemblies in a hot and humid climate. Left side: exterior, right side: interior. 25.4 mm equals 1”.

Moisture Performance Simulations Under Synthetic Weather Conditions

Figure 5 shows the expected moisture performance of selected wall assemblies under the synthetic weather conditions in Miami, FL between May 17 and June 17. In these simulations we chose to set the temperature and relative humidity inputs for the interior boundary conditions lower than those in ASHRAE Standard 160 to increase the hygrothermal gradients imposed across the wall assembly, which maximizes the inward vapor drive during our short, 1-month testing timeframe. The air change rate between the cavity and the outdoors was set to a value of 10 ACH. Concurrent spatial variations in relative humidity and moisture content of the back wall behind the WRB reveal that the most vulnerable locations for moisture accumulation are the exterior surface of the OSB and the exterior surface of the interior gypsum board.

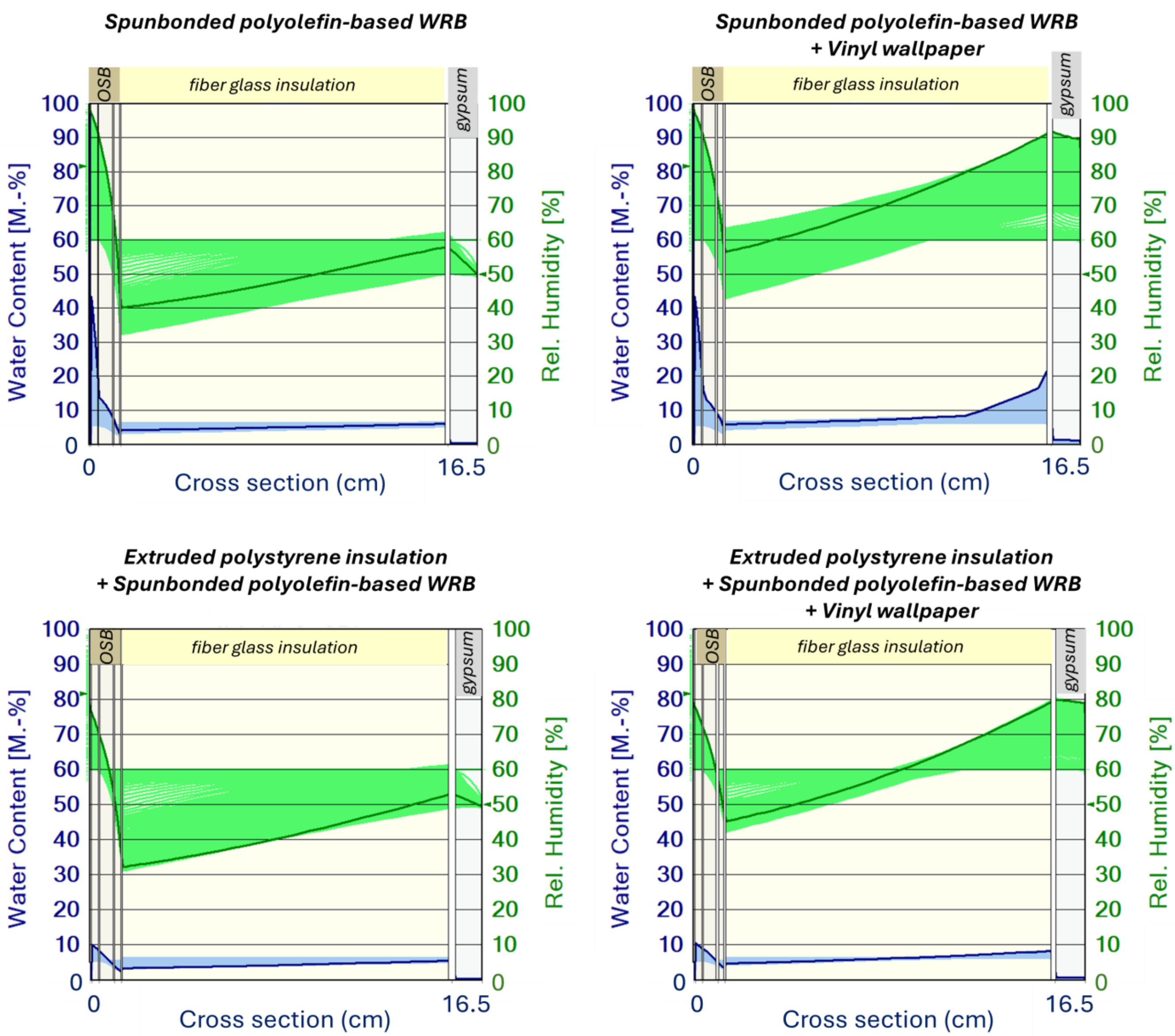

Figure 5 Comparisons of simulated relative humidity and the moisture content values across the back wall (OSB through gypsum board) of selected wall assemblies under the synthetic weather in Miami, FL between May 17 and June 17. Lighter colors show the range, while the darker solid lines are profiles obtained at the end of the simulation. 16.5 cm equals 6 ½".

The moisture content of the OSB largely depends on the permeance of the WRB. The vapor permeable spunbonded polyolefin-based WRB allows moisture levels to rise above critical levels at the exterior surface of the OSB. The addition of extruded polystyrene insulation on the exterior side of the spunbonded polyolefin-based WRB sufficiently throttles back solar-driven vapor diffusion and is expected to keep the OSB moisture content at acceptable levels during the test period.

In accordance with previous studies (Derome and Saneinejad 2010; Carmeliet and Derome 2012), low-permeance vinyl wallpaper (1 US perm; 57 ng m^{-2} s^{-1} Pa^{-1}) significantly increases the moisture risk for the exterior surface of the interior gypsum board. Moisture driven through the vapor permeable spunbonded polyolefin-based WRB accumulates within the wall due to the low permeance of the interior side of the wall assembly. Even if vinyl wallpaper is clearly not recommended in a hot and humid climate, its use in these laboratory settings may be constructive for model validation of solar-driven moisture diffusion. Testing of walls with low permeance interior finishes will generate experimental data with substantially different moisture dynamics than moisture-safe assemblies.

CONCLUSION

We have established the framework for laboratory measurements of wood-frame walls with brick cladding and OSB sheathing in a one-of-a-kind analytical chamber, the CARWASh, under a full range of exterior boundary conditions that closely mimic the rate, magnitude, and sequence of real weather events in Miami, FL. Testing and validation will be accomplished in the next phase of the study. We hope to extrapolate the validated results over longer timeframes and extend them to different wall assemblies. Finally, we will assess moisture performance and implied risk for mold growth at vulnerable locations of the wall assemblies using the recently developed Dose-Response Simple Isopleth for Mold (DR SIM) model (Boardman et al. 2023). The results overall are intended to assist building designers in their efforts to identify and mitigate the risk of moisture accumulation in different U.S. climates under various moisture load conditions.

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