Thermal Performance of the Exterior Envelopes of Whole Buildings XIV International Conference, Clearwater Beach, FL., Dec. 9-12, 2019, Buildings XIV International Conference, pp. 887-894; 2019

Hygrothermal Modeling of Wall Drying after Water Injection

Charles R. Boardman
Associate Member ASHRAE

Samuel V. Glass, PhD
Member ASHRAE

Kingston Chow

Borjen Yeh, PhD, PE

ABSTRACT

Hygrothermal models are commonly used for prediction and evaluation of wall assembly moisture performance. Drying and redistribution of moisture are important to consider because they mitigate the effect of water intrusion during construction and throughout the service life of the building. In this study we compare simulations with measurements for two out of eight different residential wood-frame wall assemblies, in two orientations, with different kinds of insulation outboard of the oriented strand board (OSB) sheathing, in the cold climate of Madison, WI. Over two years we collected weather and moisture content data, challenging the wall systems three different times with water injections to assess drying potential of the different walls. These injections placed 40 g (0.088 lb) of water each day, over several days, on a paper towel fixed to the inner surface of the OSB. Water moves into and through the OSB, but also laterally away from the injection site, and evaporates into the wall cavity air raising the relative humidity. This is inherently a three-dimensional process which is challenging for one-dimensional modeling to capture. We introduce a custom moisture source and sink method to allow WUFI Pro to match the experimental data following water injection. This technique should be useful for assessment of drying potential during wall design and analysis.

INTRODUCTION

Long-term moisture performance of exterior wall assemblies is a key consideration for contemporary energy-efficient structures. Adding continuous exterior insulation has become a common strategy to improve overall thermal performance in North American above-grade exterior wall assemblies in both retrofit applications and new construction. Although considerable research has been conducted on exterior insulation in wood-framed walls, further work is needed to provide a quantitative basis to minimize the risk from moisture intrusion and associated durability issues. A joint research project was initiated in 2014 by APA – The Engineered Wood Association and the USDA Forest Service, Forest Products Laboratory, to study the hygrothermal performance of split-insulated wall assemblies using a combination of different interior vapor retarders and continuous exterior insulation in the cold climate location of Madison, Wisconsin, USA. This paper reports on techniques used to allow hygrothermal modeling to match experimental data collected in the field study, with emphasis on the modeling of the water injection used to challenge the walls.

A brief overview of the field study is provided below, followed by a description of the hygrothermal model. Key to the injection model are physical insights regarding moisture redistribution and drying in the oriented strand board (OSB) sheathing onto which the water injections occur.

Drying and redistribution of moisture are important considerations for the building envelope because they mitigate the effect of water intrusion. Moisture performance analysis of building envelope assemblies using hygrothermal simulation often introduces unintentional moisture sources such as rain leakage to assess the assembly's tolerance (e.g., ASHRAE 2016). Although a variety of methods have been developed to introduce water into wall

Charles R. Boardman is a general engineer, Samuel V. Glass is a research physical scientist at the US Forest Service Forest Products Laboratory, Madison, WI, USA. Kingston Chow was an engineer, Borjen Yeh is director of technical services at APA – The Engineered Wood Association, Tacoma, WA, USA

assemblies in a controlled manner and study the moisture response, there is little research on simulation methods that capture the drying and redistribution behavior in a way that is realistic yet simple enough to be practical.

The wetting method used here involves injecting water into a paper towel stapled to the sheathing. Van Straaten (2003) conducted a brief laboratory study to investigate moisture redistribution in wood fiberboard sheathing using this method. He found that water moved rapidly through the thickness of the sheathing but very slowly in the lateral direction along the sheathing length; moisture pins outside the wetted area showed no increase in moisture content over a period of three days.

In laboratory drying experiments with OSB sheathing, however, Maref et al. (2010) noted a significant redistribution of moisture. The wetting method was different and apparently resulted in wetter areas at the top of an OSB panel and drier areas at the bottom. The local moisture content in the drier bottom areas increased over the first five days of the 30-day experiment. Although the mechanism of this redistribution was not clear, a possible explanation is lateral diffusion within the sheathing. Karagiozis (1998) found that moisture transfer in the lateral direction in OSB is 5 times higher than through the panel.

Field experiments using low-permeance continuous exterior insulation (Smegal and Lstiburek 2013, Boardman et al. 2019) have found that local moisture pin readings after water injections decrease more rapidly than anticipated, likely because of redistribution within OSB sheathing and inward drying under certain conditions.

Research objectives in this study were to assess and improve hygrothermal model predictions using measured field data with a focus on handling the difficult case of moisture injection using a one-dimensional (1D) model.

FIELD MEASUREMENTS

Two years of field measurements were taken in a test hut located in the cold climate of Madison, WI. Full details of the research facility and results are reported in Boardman et al. (2019). Figure 1 shows a detail of sensor placement in a test structure cavity constructed with nominal 2 x 6 in (38 x 140 mm) lumber and sheathed with 7/16 in (11 mm) OSB.

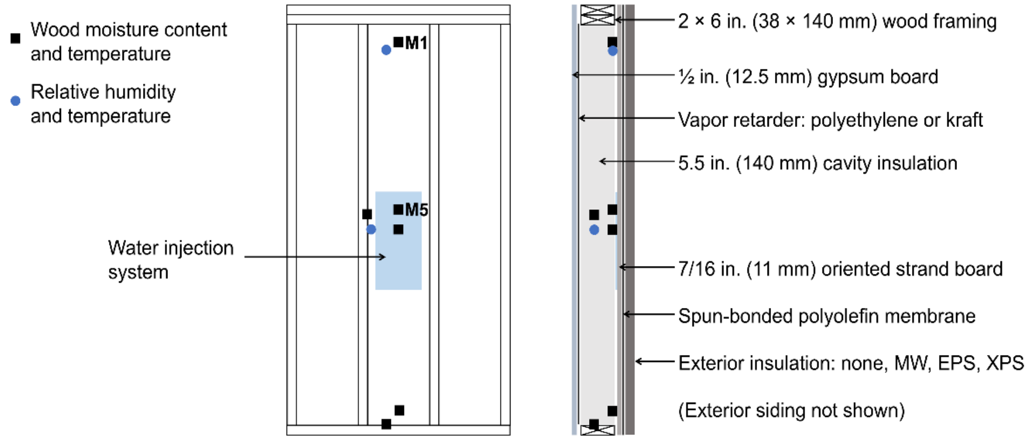

Figure 1 Sensor placement in the wall with labels showing moisture pins M1 and M5 for comparison to models.

All wall assemblies included vinyl siding, spun-bonded polyolefin house wrap, OSB, fiberglass batt cavity insulation R-21 (3.7 m^2·K/W), and painted interior gypsum drywall. Test bays differed in the type of interior vapor retarder, and exterior continuous insulation (CI) including: none; 1.5 in. (38 mm) mineral wool (MW) with resistance

R-6 (1.1 $m^2 \cdot K/W$); 1.5 in. (38 mm) expanded polystyrene (EPS) with resistance R-6 (1.1 $m^2 \cdot K/W$); 1 in. (25 mm) extruded polystyrene (XPS) with resistance R-5 (0.88 $m^2 \cdot K/W$). This paper models wall 2 (No CI, poly) and 7 (XPS, poly) both of which had a polyethylene interior vapor retarder.

Each test bay was subjected to a water injection sequence three times during the two-year study, in addition to the variable indoor relative humidity and outdoor conditions. Each injection sequence placed 40 g (0.088 lb) of water per day onto a paper towel stapled to the interior OSB surface. The strongest injection lasting 5 days occurred in winter, while the earlier fall injection lasted 3 days and the later spring injection 4 days.

Each test bay had an identical set of sensors installed in the central cavity measuring wood moisture content (MC, percentage based on dry mass), relative humidity, and temperature. Pin-type sensor pairs were placed in the OSB measuring temperature and resistance to determine MC using the calibration of Boardman et al. (2017). Two of these sensors were in the field of the paper towel and hence responded strongly to the water injections, while another was near the top of the cavity far from the paper towel. Hygrothermal model predictions are provided for both sensor locations, but only two test bays are examined in this paper. A later report will explore bays with kraft vapor retarders and other exterior insulations. Relative humidity and temperature measurements were also taken of indoor and outdoor conditions to provide the boundary conditions for the hygrothermal model.

HYGROTHERMAL MODEL DESCRIPTION

The hygrothermal model was implemented in WUFI® Pro 6.2 (WUFI Home 2018) using a fine grid (100 or more elements). The short-wave radiation absorptivity of the white vinyl siding was set to 0.12 without using explicit long-wave emission. Other material properties came from the included databases with exceptions noted below. Climate conditions were supplied as measured and numerics were set for both heat and moisture transport with increased accuracy and adapted convergence.

The material layers for the base case (No CI, poly) are listed in Table 1. Properties of several materials were customized. The permeance of the vinyl siding was modified to 40 U.S. perms (2289 $ng/Pa \cdot s \cdot m^2$) as an effective permeance to account for a vapor impermeable material but air permeable assembly (Building Science Corporation 2013). OSB properties are described below. The water injection layer was added inside the OSB to provide a receptor for simulated water injection, with a high moisture storage capacity. The RH monitoring layer was introduced to facilitate relative humidity and temperature monitoring at the location of the physical sensor just inside the OSB. Material properties of these two layers were modified to have negligible heat capacity and minimal resistance to vapor and heat transfer, to limit interference with model flows.

Table 1. Material Layers in Base Case Model

Layer	Thickness, mm (in.)
Vinyl siding*	1.1 (0.04)
Spun Bonded Polyolefin Membrane	1 (0.04)
OSB* (outer layer)	2.5 (0.10)
OSB* (core)	6.1 (0.24)
OSB* (inner layer)	2.5 (0.10)
Water injection layer*	1 (0.04)
Air Layer 5 mm; without additional moisture capacity	5 (0.20)
RH monitor layer*	1 (0.04)
Fiberglass	140 (5.51)
Polyethylene Membrane	1 (0.04)
Interior Gypsum Board	12.5 (0.49)

* Material with customized properties

OSB was modeled as three layers to resolve differences in MC through the depth and facilitate comparison with the measured values, which used pairs of screw through the full depth of the OSB (and register the highest MC). Further, the OSB material properties (Table 2) were modified from the standard OSB in the North American Database to allow a better fit with the experimental data and reflect measured values. Bulk density and moisture storage function were based on measurements from a prior study (Boardman et al. 2017). Thermal properties were based on measurements for OSB with a similar density (Igaz et al. 2017). Most significantly the water vapor diffusion resistance factor of OSB was reduced as shown in Figure 2.

Table 2. OSB Properties

Property	Modeled Value	Database Value
Bulk density, kg/m^3 (lb/ft^3)	534 (33.4)	650 (40.6)
Specific heat capacity, J/kg·K (Btu/lb·°F)	1280 (0.306)	1880 (0.449)
Thermal conductivity, W/m·K (Btu·in./h·ft^2·°F)	0.084 (0.58)	0.092 (0.64)

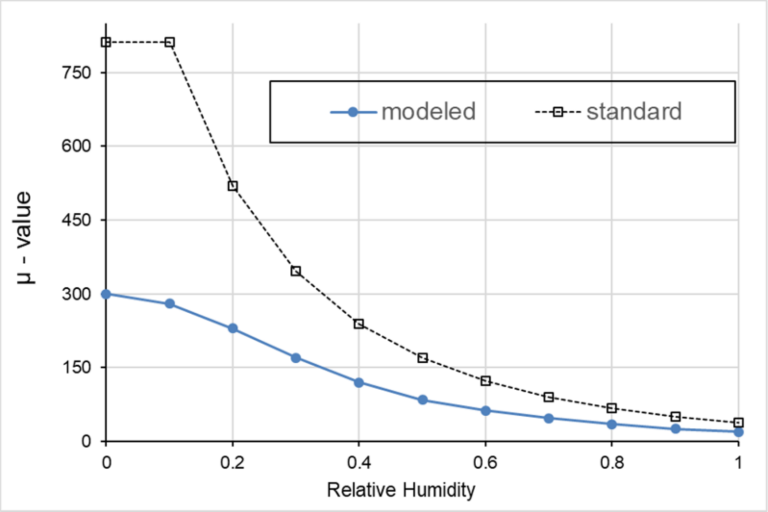

Figure 2 OSB vapor diffusion resistance factor (μ-value) as a function of relative humidity.

Moisture source and sink methodology

Each wall assembly was simulated using a pair of 1D models: the first, a "large" injection model, representing the vicinity of the water injection and the second, a smaller "coupled" injection model, representing the rest of the wall. The simulated OSB moisture content in each case was compared with measurements in each location: within the field of the water injection towel (M5) and near the top plate, far from the injection site (M1).

In the large injection model, a custom moisture source was introduced in a thin high-water-capacity layer next to the inner OSB layer to represent the paper towel used for actual injection. The injection schedule spread 40 g (0.088 lb) of water out across the 24-hour day to avoid oversaturation in the model, which was found to be a problem when sourcing all the moisture in one hour. In this large injection model, the source was 0.51 kg/(m^2·day) or 0.1 lb/(ft^2·day), corresponding to spreading the 40 g (0.088 lb) of water over the towel wetting area of approximately 11 in. × 11 in. (0.28 m × 0.28 m). The large injection case also needs a moisture-removing sink to model the OSB moisture redistribution that occurs when the paper towel gets wet. Without a sink the simulation significantly over-predicted OSB MC. This sink was placed in a 1 mm (0.04 in.) layer only 0.5 mm (0.02 in.) from the inner surface of the inner OSB layer. This sink placement gives good agreement with measured data but was chosen primarily for simplicity. The shape of the moisture sink is discussed in more detail subsequently.

The effect of water injection on the OSB sheathing away from the towel was modeled with a smaller "coupled" injection strength which was based on the mass of water removed by the sink in the large injection. This redistribution from the large injection model spreads the water across the full OSB surface of 14.5 in. × 82 in. (0.37 m × 2.1 m). The physical idea is that the moisture leaving the towel area is the source for the moisture in the rest of the system, thus coupling the two models. For this smaller injection the moisture source strength was the sink strength from the large injection case scaled by the ratio of the towel area to the area of the rest of the OSB (1/10). No sink was used in the coupled case.

The moisture sink strength in the large injection model was adjusted so that 55 to 85 percent of the water injected was removed by the sink. Final tuning of that sink strength was done by comparing predictions to the measured data, but 85% is a good first guess. Also important is the shape of that moisture sink. We hypothesize from other studies that the lateral movement of moisture away from the injection site is strong at first, and then rapidly trails off. In related work in progress we have measured the mass of a wall section while injecting water and measuring the OSB MC both in the field of the paper towel and outside that field. This allows comparison of water leaving the system (direct mass loss) with what the moisture pins record (mass loss and transfer away from measurement area). A subsequent report will give details and modeling results for those investigations. Relevant for this paper is that the functional shape of the moisture loss due to migration outside the paper towel can be characterized by a stretched exponential curve. This shape was used to characterize the MC decay in the field study (Boardman et al. 2019), which gives further detail regarding τ, the time constant, and c, a shape parameter which determines the amount of stretch. Equation 1 shows the functional form. The three sink functions which correspond to the three injection periods share the same c=0.79 and τ=75 h for both wall configurations tested. The scale factor *K* adjusts the total strength. Figure 3 shows the sink strength versus time after injection for the base case of 85% removal of total injection.

$$f(t) = K \ {\frac{1}{1 + ct/\tau}}^{\frac{1}{c}} \qquad (1)$$

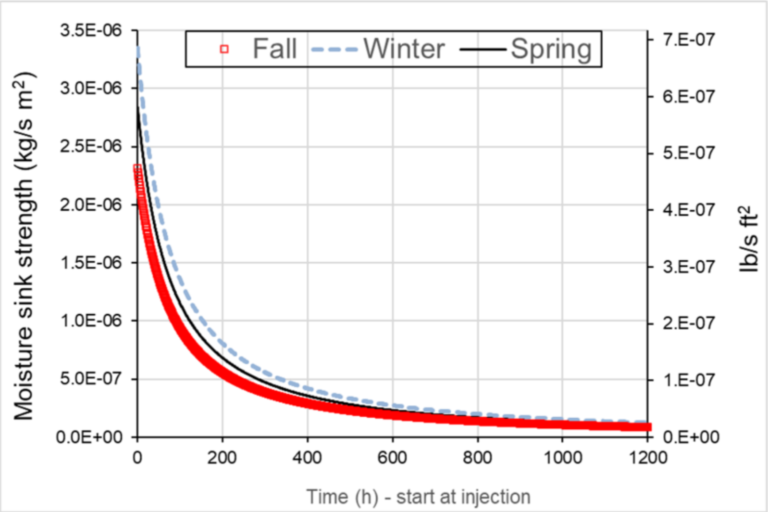

Figure 3 Shape of sink function for three injections in base case wall.

RESULTS AND DISCUSSION

Figure 4 plots the simulated OSB moisture content and measured values for both walls. The top row plots the large injection case in the field of the paper towel, while the bottom row plots the coupled redistribution case far from the water injection site. All plots show good agreement between predictions and moisture pin measurements, with root-mean-square-error (RMSE) below 3.1% MC as discussed subsequently. The model is, not surprisingly, sensitive to the strength of the moisture source and sinks. Added insulation can slow drying and makes the model more sensitive to these values. Similarly, matching the winter performance is the most difficult since that encompasses the largest injection, and the cold slows drying compared to the spring or fall injections. The lower right of Figure 4 shows two cases of model prediction for wall 7 (XPS, poly). In the standard coupled case (dark blue dashed) using the standard area reduction factor (10) the predicted MC rises slightly above the measured during the winter injection. The lighter blue solid line labeled WUFI MC (half) shows the better fit achieved by reducing the injection to half the original strength. Physically this is reasonable since moisture pin M1 was far from the injection site and the redistributed water was not actually uniformly applied across the whole OSB surface. In making these comparisons it is helpful to have a quantitative measure. Table 3 provides the RMSE for the cases in Figure 4 and includes the same cases for the north walls.

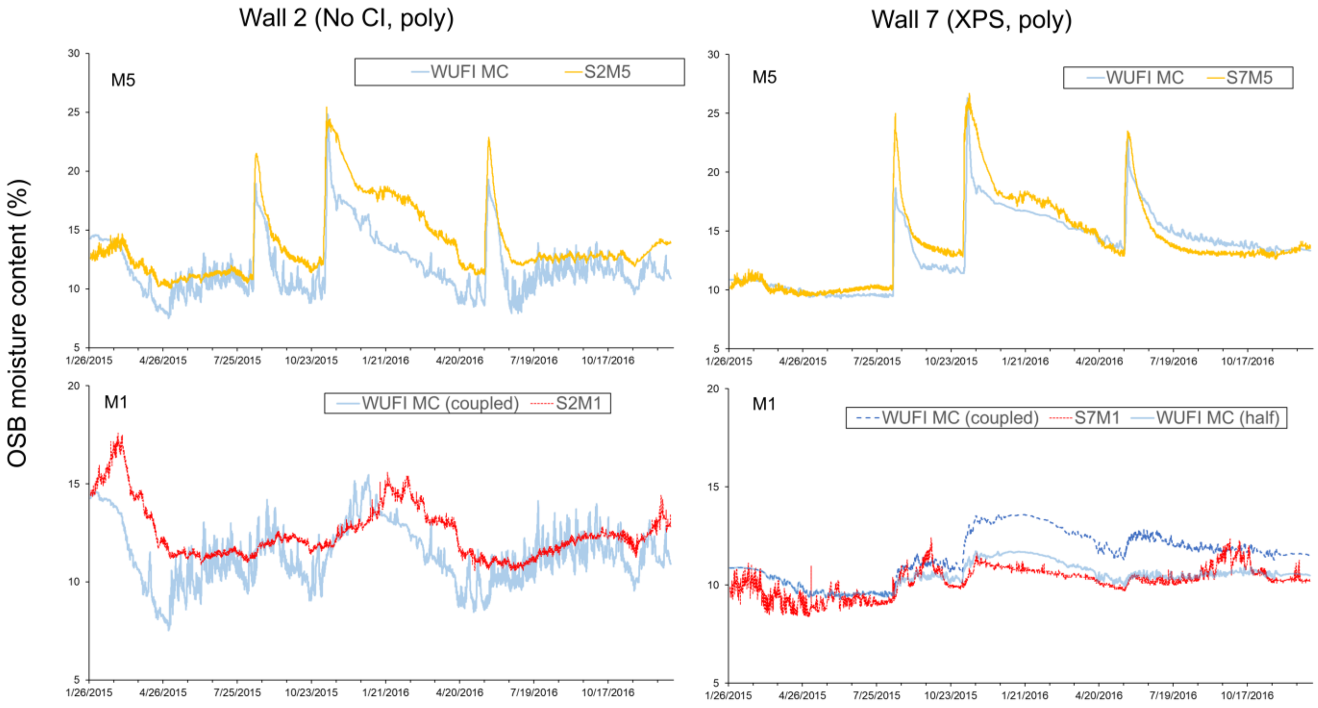

Figure 4 OSB MC model predictions versus measured values.

Table 3. Root-Mean-Square Errors for Select Walls

Exterior Insulation	Orientation	Injection Model	RMSE		
			MC, %	Temperature, °C (°F)	RH, %
No CI	South	large	2.6	1.8 (3.2)	10.5
XPS	South	large	1.5	1.4 (2.5)	16.9
No CI	North	large	3.1	1.6 (2.9)	10.5
XPS	North	large	1.4	1.1 (2.1)	19.7
No CI	South	small	1.7	1.8 (3.2)	6.4
XPS	South	small	1.6	1.4 (2.5)	9.8
XPS	South	half	0.6	1.4 (2.5)	6.1
No CI	North	small	1.0	1.6 (2.9)	6.6
XPS	North	small	2.9	1.1 (2.1)	12.4
XPS	North	half	1.7	1.2 (2.1)	8.4

Also included in Table 3 are the RMSE values from temperature and relative humidity predictions compared to a sensor just inside the OSB inner surface. The RH readings often have larger errors around the time of injection because the model RH rises higher than the measured values. There is further redistribution of moisture from the cavity air to the structural lumber, not accounted for in this 1D model, which causes the measured RH to have a smaller rise after injection. RH prediction might be improved by adding an additional moisture sink in the fiberglass but was not explored in this paper.

The model MC predictions are influenced by temperature modeling which must be close to measured temperatures before the MC can be realistic. Thus, the OSB thermal conductivity was reduced as shown in Table 2 to reflect our lower density OSB and reduce the temperature RMSE. Further, the temperature predictions are sensitive to the short-wave radiation absorptivity of the cladding. The model is also sensitive to the moisture source and sink strengths. One example was already given in Figure 4 (coupled model) which showed the effect of two different source strengths on MC prediction in wall 7 (XPS, poly). In the large strength injection case, the sink strengths and shapes can be adjusted from the default 85% removal and τ=75 h to better match the measured data. For example, in wall 2 (No CI) the default sink removes too much water and causes the prediction to fall short of the measured peak during injections 1 (fall) and 3 (spring), while it dries out too quickly during winter. Figure 5 shows the effects of reducing the removal to 55% and decreasing τ to 55 h for injections 1 and 3, while reducing removal to 70% and increasing τ to 120 h for injection 2 (winter).

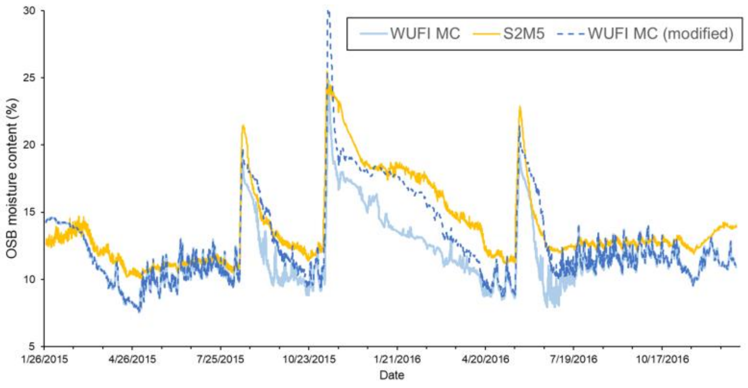

Figure 5 Moisture content predicted, default and modified, compared to measurement for wall 2 (No CI, poly) using large strength injection and different sink strengths.

Adjusting the sink profile allows a closer match to the peak MC during fall and spring, but overshoots the peak in winter, reducing the overall RMSE from 2.6% to 1.6% MC. Regardless, the default case is still a reasonable match and could be helpful during design analysis when measured data is not available.

CONCLUSION

A simple one-dimensional hygrothermal model was modified to account for the effects of lateral moisture distribution in OSB sheathing after intentional water injection. In WUFI this was accomplished using select moisture sources and sinks of appropriate strength. Examples of default strengths and shapes were provided to model MC readings both at and far from the injection location in walls with and without exterior insulation. As expected, model results were sensitive to material properties. In WUFI the temperatures were especially sensitive to radiation balance on the cladding. Modeling OSB in three layers allows a better match to moisture pins which read the highest MC inside the OSB. If measured MC values are available, the model can be tuned to provide further insight into the physics of moisture movement in the OSB.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the help of many colleagues during this investigation, especially Robert Munson of the Forest Products Laboratory. This work was funded by the U.S. Forest Service and APA – The Engineered Wood Association through Joint Venture Agreements 14-JV-11111136-054 and 17-JV-11111135-033.

REFERENCES

ASHRAE. 2016. ANSI/ASHRAE Standard 160-2016, *Criteria for Moisture-Control Design Analysis in Buildings*. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.

Boardman, C. R., S. V. Glass, and P. K. Lebow. 2017. Simple and accurate temperature correction for moisture pin calibrations in oriented strand board. *Building and Environment* 112: 250-260. doi:10.1016/j.buildenv.2016.11.039.

Boardman, C. R., S. V. Glass, R. Munson, B. Yeh, and K. Chow. 2019. *Field moisture performance of wood-framed walls with exterior insulation in a cold climate*. Research Paper FPL-RP-698. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 40 p.

Building Science Corporation. 2013. *Info-312: Vapor Permeance of Some Building Materials*. Accessed April 15, 2019. https://www.buildingscience.com/documents/information-sheets/info-312-vapor-permeance-some-materials.

Igaz, R., L. Kristak, I. Ruziak, M. Gajtanska, and M. Kucerka. 2017. Thermophysical properties of OSB boards versus equilibrium moisture content." *BioResources* 12(4): 8106-8118.

Karagiozis, A. N. 1998. Applied moisture engineering. *Thermal Performance of the Exterior Envelopes of Buildings VII*. Clearwater Beach, FL: ASHRAE Proceedings. 239-251.

Maref, W., M. A. Lacasse, and D. Booth. 2010. Experimental assessment of hygothermal properties of wood-frame wall assemblies—moisture content calibration curve for OSB using moisture pins. *Journal of ASTM International* 7(1): 1-12. doi:10.1520/JAI102091.

Smegal, J., and J. Lstiburek. 2013. *Hygric Redistribution in Insulated Assemblies: Retrofitting Residential Envelopes Without Creating Moisture Issues*. Somerville, MA: Building Science Corporation.

Van Straaten, R. 2003. *Measurement of ventilation drying of vinyl siding and brick clad wall assemblies*. M.S. thesis, Waterloo, Ontario, Canada: University of Waterloo, Department of Civil Engineering.

WUFI Home. 2018. Fraunhofer Institute for Building Physics. Accessed April 11, 2019. https://wufi.de/en/.