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Effect of rain leakage on hygrothermal performance of highly insulated wood framed walls: a stochastic approach

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Abstract

Wind-driven rain is one of the most important moisture sources that may lead to moisture damage risks of building envelopes, particularly when the rainwater unintentionally infiltrates into the envelope assembly through defects of the wall components. This paper proposes a stochastic modelling approach to evaluate the impact of rain infiltration on hygrothermal performance of highly insulated wood framed walls, including an I-joist deep cavity wall, two exterior insulated walls, and a conventional 2x6 stud wall as the baseline wall. The stochastic hygrothermal models of the walls are created based on the uncertainties of material properties and rain deposition factor under different scenarios with rain infiltration deposited at different locations of the wall assembly. The stochastic simulation results show that the rain water deposited on water resistive barrier does not cause any moisture damage risk, but there is a significant risk when the rain water is directly deposited on the exterior or interior surface of wood sheathing, and the interior deposition has the highest risk.

Key words: rain leakage, hygrothermal performance, highly insulated wood-frame wall, stochastic modelling, mold growth risk

50 **Nomenclature**

Symbol	Parameter	Unit
A	Water absorption coefficient	$\text{kg/m}^2\cdot\text{s}^{0.5}$
c	Specific heat capacity of dry material	$\text{J/kg}\cdot\text{K}$
D_{ww}	Moisture diffusivity at saturation state	m^2/s
F_{D}	Rain deposition factor	-
F_{E}	Rain exposure factor	-
w_{f}	Capillary saturation water content	kg/m^3
Greek symbols		
α_{l}	Long-wave radiation emissivity	-
α_{s}	Short-wave radiation absorptivity	-
α_{ex}	Exterior heat transfer coefficient	$\text{W/m}^2\cdot\text{K}$
α_{in}	Interior heat transfer coefficient	$\text{W/m}^2\cdot\text{K}$
β_{ex}	Exterior vapour transfer coefficient	s/m
β_{in}	Interior vapour transfer coefficient	s/m
θ_{por}	Porosity	-
μ_{Dry}	Vapour diffusion resistance factor at dry state	-
ρ	Bulk density of materials	kg/m^3

1. Introduction

Wind-driven rain is one of the most important moisture sources that affect the hygrothermal performance and durability of building envelopes (Marsh 1977; Blocken and Carmeliet 2004). Hazleden and Morris (1999) summarized the measures of controlling rain water as 4Ds principle: Deflection, Drainage, Drying and Durable. They suggest that the properly designed deflection and drainage systems are able to theoretically reduce the rain infiltration to less than 1% of the rain impinging onto the exterior cladding. However, rain water is possible to infiltrate into wall assembly due to the defects of the building envelope assembly (mostly occurred at the junctions of wall-window, wall-exterior electrical outlet or wall-ventilation duct penetration etc.) caused by poor detailed design, faulty workmanship during construction and lack of proper maintenance (Beer and Smith 1998; Lies and Faith 1998; Zwyer et al. 1998). The rain infiltration can cause serious moisture damage even with a very small infiltration rate (for example, one drop per hour directly on the drywall or structure sheathing) if the wall components cannot be dried quickly (Straube 2002).

In the past decades, many studies have been carried out to investigate the rain infiltration and its impact on hygrothermal performance of building envelopes. Most of them are experimental studies, which generally aim to evaluate the water tightness of the building envelope components or quantify the amount of the rain infiltration (Granne 2001; Derome et al. 2007; Lacasse et al. 2009; Van Straaten et al. 2010; Bossche et al. 2011; Olsson and Mjornell 2012; Perez-Bella et al. 2013a 2013b; Perez-Bella et al. 2014; Boardman and Glass 2013; Olsson 2015; Bossche and Janssens 2016; Recatala et al. 2018; Olsson 2018). The water tightness test can be performed with a specified water spray rate and air pressure to simulate wind driven rain effect on the building envelope, then a pass or fail evaluation will be provided for the building envelope components

(ASTM 2000a; ASTM 2000b; ASTM 2000c). NRC researchers applied the test methods to quantify the water leakage rate at the defects of different wall components (such as the junctions of wall-window, wall-exterior electrical outlet and wall-ventilation duct) with different water spray rates and air pressures. It was found that the water penetration generally increased with the increase of water spray rate (Bomberg et al. 2002; Lacasse et al. 2003). However, these water spray rates and air pressures did not reflect real climate conditions. Tesdale-St-Hilaire (2006) developed a wetting protocol that correlated Montreal climate conditions to establish water infiltration load to a wood-frame wall. The water tightness test showed that water infiltration through the wall-window junction is about 4% - 5% of the rainwater impinging on the window surface depending on the sizes of the defects. Recently, Olsson (2017) summarized rain infiltration rates at building façade details from four laboratory studies. It was concluded that under heavy wind-driven rain condition, the amount of water infiltration can be up to 2% of the applied water load even in small invisible deficiencies.

For simulation study, ASHRAE 160 (2016) proposed that 1% of the rain water reaching the exterior cladding surface can be deposited on the exterior surface of water resistive barrier to simulate the rain leakage. However, the specified amount and position of the rain leakage cannot cover various situations, which may be worse than that prescribed in the standard. Kunzel and Zirkelbach (2013) applied ASHRAE 160 method on External Thermal Insulation Composite System (ETICS) to simulate moisture performance under rain leakage. Simulations were performed for five selected locations, where the amount of wind-driven rain in the most exposed orientations are ranging from 112 l/m²·a to 193 l/m²·a. The moisture sources of 1%, 2%, 3% and 4% wind-driven rain were deposited evenly on the OSB sheathing. It was found that the 1% and 2% of rain leakage does not result in any moisture issue, the 3% and 4% of rain leakage lead to a

risky moisture content (higher than 20%) of OSB sheathing. Ott et al. (2015) also evaluated the ASHRAE 160 method by depositing 1% wind-driven rain on two positions: the exterior surface of WRB and the exterior surface of insulation, which is behind the WRB. It was found that depositing the rain leakage on the exterior surface of WRB does not give the satisfying results since the defect of the WRB is not taken into account. While, depositing the rain leakage behind the WRB increases the moisture content of insulation and adjacent layer by factor of 20-30, which is abnormally high. Carboneze et al. (2015) compared different ways of simulating rain leakage-point moisture source and uniform load through 2D hygrothermal simulation. It was found that uniform load approach is more proper for occasional rain leakage, while point source method should be applied at the places where water is likely to accumulate.

In summary, it is commonly acknowledged that rain infiltration is inevitable and significantly affect the durability performance of building envelopes. Many experimental studies have been carried out to investigate the water tightness of building envelope components and quantify the amount of rain infiltration, but there is still a large uncertainty among different experimental studies due to various influential factors such as the position and the size of the defects, the environmental condition applied to the tested envelopes. Simulation studies showed that the standardized rain leakage simulation method (ASHRAE 160-2016) is not able to reflect the worst scenarios of rain leakage, and the moisture performance of the building envelope is very sensitive to the amount and position of the rain leakage. However, there is a lack of simulation study taking into account the uncertainties of the rain infiltration to evaluate the hygrothermal performance and moisture problem risks of the building envelopes.

This paper investigates the impact of rain infiltration (with consideration of its uncertainties: the amount and position) on the hygrothermal performance and mold growth risks of highly insulated

wood framed walls through a stochastic modelling approach. The 1D hygrothermal models of the highly insulated wood framed walls were created and validated in previous study (Wang and Ge 2017). The stochastic modelling has been performed to evaluate the mold growth risks under different types of moisture loads (air leakage and rain leakage) (Wang and Ge 2018). But it was assumed the infiltrated rain water is deposited on the exterior surface of wood sheathing, which is not the worst scenario. In this paper, the material properties of wood sheathing and insulations, and rain deposition factor are considered as stochastic variables. To further investigate the impact of rain infiltration, the positions of the rain leakage are considered as scenario variables with three states: the water resistive barrier, the exterior surface of the wood sheathing, and the interior surface of the wood sheathing, which represents three separate scenarios. For each scenario, the stochastic simulations are performed for mold growth risk assessment.

2. Method

The stochastic modelling approach developed by Wang and Ge (2018) is applied to investigate the impact of rain infiltration on highly insulated wood framed walls. This section presents the specific methods of this approach, including hygrothermal base models setup and stochastic models setup.

2.1 Hygrothermal base models setup

To investigate the hygrothermal performance of highly insulated wood-frame walls, thirteen highly insulated wood-frame walls were tested on a Building Envelope Test Facility located in Southern Ontario Canada (Fox 2014; Trainor 2014). Four of the test walls are selected for the stochastic modeling in this paper. They are I-joist wall, two types of exterior insulated walls (one with polyisocyanurate exterior insulation, and the other with mineral wool exterior insulation), and the conventional 2x6 baseline wall. Table 1 shows the differences of the framing, insulation and interior vapor barrier of the selected walls, and Figure 1 shows the plan view of the walls. All the

walls have the same exterior cladding system, which includes 11 mm fiber cement siding and 19 mm strapping/drainage space. The structural boards are 11 mm OSB sheathing, and interior finishes are 12.5 mm gypsum board.

The hygrothermal models of the investigated walls are created by DELPHIN, a simulation program for coupled heat, air and moisture transport in porous building materials. The mean values of the material properties, boundary conditions and monitored indoor and outdoor climatic conditions are used as the input parameters of the models, which are validated by comparing the simulation results with the measurements (Wang and Ge 2017). Table 2 and Table 3 show the material properties and boundary conditions of the validated models.

The wind-driven rain is calculated based on the semi-empirical model in ASHRAE 160 (2016).

The equation of the semi-empirical model is presented as follows:

$$r_{bv} = F_E \cdot F_D \cdot F_L \cdot U \cdot \cos\theta \cdot r_h \quad (1)$$

where

F_E - rain exposure factor

F_D - rain deposition factor

F_L - empirical constant, 0.2 (kg·s/m³·mm)

U - hourly average wind speed at 10m (m/s)

θ - angle between wind direction and normal to the wall

r_h - rainfall intensity, horizontal surface (mm/h)

As base models, the rain leakage is simulated by depositing 1% of wind-driven rain on the water resistive barrier, which follows the prescription in ASHRAE 160 (2016).

2.2 Stochastic models setup

The stochastic models are created based on the stochastic hygric material properties and rain deposition factor, and Latin Hypercube Sampling method is applied to generate the stochastic models (Wang and Ge 2018). The stochastic variables of the hygric properties follow normal distribution, the mean value and standard deviations are listed in Table 4. The material property functions are scaled by multiplying coefficients: $\text{parameter_stochastic}/\text{parameter_mean}$. The rain deposition factor is ranging from 0.35 to 1 and follows a uniform distribution, to reflect the variability of rain leakage. Simulations are performed under climate condition of Vancouver, which represents warm and humid climate zone with high rainfall amount and may lead to higher moisture problem risks than South Ontario. The weather data from Canadian Weather Year for Energy Calculation (CWEC) is used for five-year simulation.

The orientation and position of the rain leakage are considered as scenario variables. The orientation has two states- south and east, which receives different level of wind-driven rain (south orientation, $237 \pm 114 \text{ l/m}^2\cdot\text{a}$; east orientation, $605 \pm 291 \text{ l/m}^2\cdot\text{a}$). The position of rain leakage has three states: 1) water resistive barrier (WRB), which represents the situation prescribed by ASHRAE 160 (2016); 2) the exterior surface of OSB, which considers the rain water pass through the defects of WRB; 3) and the interior surface of OSB, which is the worst situation of the rain leakage. The assumed three states represent different scenarios with different mold growth risk level- safest (scenario 1), medium (scenario 2) and worst (scenario 3). To simulate the rain leakage, the OSB is discretized into 16 elements with variable size, the exterior and interior elements have the minimum size of 0.3 mm. The water resistive barrier is discretized into 3 elements (0.3 mm exterior element, 0.4 mm middle element and 0.3 mm interior element). For WRB rain deposition (scenario 1), the rain leakage is deposited on the exterior element of WRB. For the OSB rain

deposition, the rain leakage is deposited on the exterior or interior elements to simulate scenario 2 and 3. The moisture content level and mold growth index at the interior side of OSB (the element close to the interior rain deposition layer) are observed for performance evaluation. Figure 2 shows the rain leakage deposition positions in the hygrothermal model.

In summary, there is a 2x3 factorial design, and 6 scenarios which represent different levels of wind-driven rain and positions of rain leakage are generated. For each scenario, 100 stochastic models are generated according to Latin Hypercube Sampling method. Table 5 shows the organization of the scenario variables and stochastic variables. The stochastic simulations are performed in MATLAB. DLPHIN's project file are modified repeatedly to generate the stochastic models, and simulation engine is called to run each stochastic model.

3. Results

3.1 Stochastic moisture content

Figure 3 shows the stochastic results for scenario 1, which the rain leakage is deposited on the water resistive barrier. It can be seen that the moisture content for all the walls do not exceed 20% during the simulation period, and the moisture content levels are similar with the scenario without rain leakage. It can be said that the water resistive barrier is effective to protect the OSB sheathing from the rain water, and the moisture content of the OSB sheathing will not be elevated by the rain water if it does not pass the water resistive barrier.

Figure 4 shows the stochastic moisture content of OSB sheathing with the rain leakage being deposited on the exterior surface of OSB. The moisture content of the walls are significantly higher than those of scenario 1, which indicates the water resistive barrier is a critical line of defense and the defects of water resistive barrier will result in serious moisture problem. The moisture contents of OSB in the east orientation are much higher than those of south orientation because the east

orientation receives a much higher amount of wind-driven rain than the south orientation and the solar radiation in south is also higher than that in east. It is noticed that the mineral wool wall has higher moisture content level than polyisocyanurate wall because the interior vapor barrier of mineral wool wall reduces the chance of inward drying of the infiltrated rain water. Note that the polyisocyanurate wall has polyethylene film removed.

Figure 5 shows the stochastic moisture contents of OSB sheathing under scenario 3, in which case the rain leakage is deposited on the interior surface of OSB sheathing. The moisture content of OSB are generally higher than those under scenario 2, and there are significant peaks during the rain events because the moisture content observed is from the inside of OSB - the element that is close to the interior rain leakage deposition layer as shown in Figure 2. When the rain leakage is deposited on the exterior surface of OSB, some of the deposited rain water can be transferred toward outside or stored in the OSB while moisture is transported towards the interior surface, thereby less amount of rain water reaches the interior side of OSB. Therefore, when the rainwater is deposited on the interior surface of the OSB, the MC of the sheathing is higher and the moisture problem risk is greater, and this is the worst rain leakage scenario.

Table 6 shows the maximum moisture contents and their uncertainties for the investigated walls under different scenarios. For the east orientation, which receives the highest amount of wind-driven rain, the highest moisture contents and their uncertainties of scenario 2 and 3 are much higher than those of scenario 1, while scenario 3 is slightly higher than scenario 2. Therefore, for the condition with a high wind-driven rain load, the water resistive barrier plays a more important role than the position of rain leakage for moisture content level. When the rain leakage is deposited on OSB sheathing (scenario 2 and scenario 3), the I-joist wall has lower moisture content level than the baseline wall because of the hygroscopic property of cellulose fiber, which is able to

absorb more moisture from OSB than fiberglass. For polyisocyanurate wall, the moisture content level is lower than baseline wall and I-joint wall due to the higher OSB temperature and the absence of interior vapor barrier, which allows the infiltrated rain water to be dried toward inside. The mineral wool wall has higher moisture content than polyisocyanurate wall because the interior vapor barrier restricts the drying of infiltrated rainwater towards interior. For south orientation, the moisture contents and their uncertainties of scenario 2 is slightly higher than those of scenario 1, while scenario 3 is much higher than scenario 1 and scenario 2. This means for the condition with a low wind-driven rain load, the moisture content level is more sensitive to the position of rain leakage than the effect of water resistive barrier.

3.2 Mold growth risks

The stochastic mold growth indexes are calculated for mold growth risk assessment. The mold growth indexes are calculated based on the model developed by Ojanen et al. (2010), and the sensitivity class is selected as “sensitive”, which represents the glued wooden board, PUR with paper surface and spruce. Figure 6 shows the probability density functions of the highest mold growth index over 5 years. For scenario 1, the rain leakage is deposited on WRB, the mold growth indexes are always zero over 5 years’ simulation period, therefore, the results of scenario 1 are not presented. According to ASHRAE 160- 2016, there would be a mold growth problem if the mold growth index is higher than 3, therefore, the mold growth risk is defined as the probability that the highest mold growth index is higher than 3. For the baseline wall facing to south orientation, the mold growth risk is 5% for exterior rain deposition, while 78% for the interior deposition. For east orientation, both exterior and interior rain deposition result in 100% mold growth risk, and the interior rain deposition generally has higher mold growth risk than the exterior rain deposition because of less drying potential. For I-joint wall facing the south orientation, there is no mold

growth risk when the rain leakage is deposited on the exterior surface of OSB, while the mold growth risk for the interior deposition is 48%. For the east orientation, the exterior and interior deposition have similar level of mold growth risks (98% for exterior deposition and 100% for interior deposition). For the baseline wall and I-joist wall, it can be said that the difference of mold growth risk between exterior and interior rain deposition is more significant for south orientation than east orientation. For the south orientation with smaller amount of wind-driven rain, although the mold growth risk is very low when the infiltrated rain water reaches exterior surface of OSB, there is significant mold growth risk if the infiltrated rain water reaches the interior surface. For east orientation with the highest amount of wind-driven rain, both exterior and interior rain deposition can cause serious mold growth risks.

The mold growth indexes for the exterior insulated walls facing to south orientation are always zero for both exterior and interior rain deposition, therefore, the results for south orientation are not presented. For east orientation, polyisocyanurate wall has 50% mold growth risk for exterior rain deposition, while 61% risk for interior deposition. The mold growth risks for mineral wool wall are 100% for both exterior and interior rain leakage deposition. It can be concluded that different rain leakage position does not cause significant difference of mold growth risk for exterior insulated walls, and the risk of polyisocyanurate wall which has no interior vapor barrier is much lower than that of mineral wool wall which has interior vapor barrier since the absence of interior vapor barrier allows the penetrated rain water to be dried toward inside.

It can be observed that for east orientation, the mold growth risks for baseline wall, I-joist wall and mineral wool wall are almost 100%, which means even the lowest rain factor (0.35) with 1% rain leakage will result in mold growth problem. To figure out the threshold of rain leakage level that

results in mold growth problem in east orientation, stochastic simulations are also performed for 0.5% rain leakage and 0.1% rain leakage for scenario 2 and 3.

Figure 7 shows the mold growth risks for the walls with 0.5% rain leakage for east orientation. It can be seen that for the baseline wall, the mold growth risks are still very high (as shown in Figure 7a), 95% for the exterior deposition and 100% for the interior deposition). The mold growth risks for I-joist wall are 29% for exterior deposition and 84% for interior deposition, which are lower than those with 1% rain leakage. The polyisocyanurate wall has no mold growth risk, while for mineral wool, the risk is much lower for exterior rain deposition (22%) but slightly lower for interior rain deposition (98%). For 0.1% rain leakage, only the baseline wall with interior rain leakage has mold growth risk (20%), which is presented in Figure 8.

3.3 Threshold of rain deposition factors

Table 7 and 8 show the threshold of the rain deposition factor for the walls with 1% rain leakage for both south and east orientation. The threshold is defined as the values of the rain deposition factor that are corresponding to mold growth index of 3. The rain deposition factor should not exceed these thresholds to avoid mold growth risk. For east orientation, there is no mold growth risks for all the walls for scenario 1, which there is no defects of water resistive barrier. While the mold growth risks are 100% for the baseline wall, I-joist wall and mineral wool wall for scenario 2 and 3, which means even the cases with lowest rain deposition factor still have mold growth risks. Since the lowest value of rain deposition factor is determined based on walls with flat roof but without deflection structures, the first line of defense (deflection such as overhang or balcony) is important for these walls to avoid mold growth risks in case of the defects of water resistive barrier. For polyisocyanurate wall, the threshold of rain deposition factor is 0.65 for scenario 2 and 3, which means the third line of defense (drying) is able to handle a certain amount of rain leakage,

which should not higher than that calculated by rain factor of 0.65. For south orientation, the I-joist wall and exterior insulated walls have no mold growth risk when the rain leakage is deposited on WRB or exterior surface of OSB. While the rain deposition factor for baseline wall should not higher than 0.94 to avoid the mold growth risk. When the rain leakage is deposited on the interior surface of OSB, the rain deposition factor for baseline wall should not higher than 0.48, and that for I-joist wall and mineral wool wall should not higher than 0.7. For polyisocyanurate wall, there is no mold growth risk even for the worst scenario, which means the third line of defense is able to handle the maximum amount of rain leakage for this wall at south orientation.

Table 9 and Table 10 show the threshold of rain deposition factors with 0.5% rain leakage and 0.1% rain leakage for east orientation. For 0.5% rain leakage, the baseline wall still needs the deflection structures to reduce the rain water that is deposited on the wall since the lowest rain deposition factor cannot avoid mold growth risks. The threshold of I-joist wall is increased to 0.78 for exterior deposition and 0.44 for interior deposition. The polyisocyanurate wall is able to handle the rain water penetrated through the second line of defense, even the highest rain deposition factor will not result in mold growth risk. For mineral wool wall, the rain deposition factor is increased significantly from 0.35 to 0.83 for exterior deposition, while the increase is not significant for the interior deposition (0.36). For 0.1% rain leakage, the I-joist wall, polyisocyanurate wall and mineral wool wall are able to handle the rain leakage even for the highest rain deposition factor. While for the baseline wall, the rain deposition factor should not be higher than 0.85 when the rain leakage is deposited on the interior of OSB to avoid mold growth risk, the exterior rain leakage deposition will not result in mold growth risk.

4. Conclusion

This paper investigated the impact of rain leakage on the hygrothermal performance and mold growth risks for four types of highly insulated wood framed walls using a stochastic modeling approach for Vancouver. The material properties of OSB sheathing and insulation, and rain deposition factor are considered as stochastic variables, and stochastic models are created under three rain leakage scenarios with different deposition positions of rain leakage: WRB, exterior surface of OSB and interior surface of OSB. The moisture content levels and mold growth risks at the interior side of OSB sheathing are evaluated, and the main conclusions are:

- The rain leakage deposited on the water resistive barrier does not result in changes in moisture content of wood-sheathing compared to cases without rain leakage deposited on WRB, therefore, no mold growth risks for all the investigated walls.
- The rain leakage on exterior surface of OSB result in serious mold growth risks for the east orientation, which receives the highest amount of wind-driven rain for Vancouver. While for south orientation, which receives much less wind-driven rain, there are no mold growth risks for the I-joist wall and exterior insulated walls, but a small risk for the baseline wall.
- The rain leakage deposited on the interior surface results in significant mold growth risks for all the walls in both east and south orientation, and the risks in east orientation is more serious than that in south orientation.
- For the walls facing to east orientation, the first line of defense- deflection is important to reduce the amount of rain water impinging on the exterior wall surface in case of the defects of the second line of defense- water resistive barrier. When certain amount of infiltrated rain water pass through the water resistive barrier, there would be serious mold growth risks, no

matter where the infiltrated rain water is deposited, either on the exterior or interior surface of OSB.

- For the walls facing to south orientation, which receives much lower amount of wind-driven rain and higher amount of solar radiation than east orientation, the third line of defense-drying is able to handle a certain amount of rain leakage with properly designed roof (represented by rain deposition factor) if the infiltrated rain water is deposited on the exterior surface of OSB. However, there would be significant mold growth risks if the infiltrated rain water reaches interior surface of OSB with the three level of amounts assumed and investigated in this paper.

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Figure legends:

Figure 1: Plan view of the tested walls (the figures are adapted from Fox (2014))

Figure 2: Positions of rain leakage deposition

Figure 3: Stochastic results of MC with variation of material properties and rain deposition factors (1% of wind-driven rain)_Rain Leakage on WRB

Figure 4: Stochastic results of MC with variation of material properties and rain deposition factors (1% of wind-driven rain)_Rain Leakage on Exterior Surface of OSB

Figure 5: Stochastic results of MC with variation of material properties and rain deposition factors (1% of wind-driven rain)_Rain Leakage on Interior Surface of OSB

Figure 6: Probability density functions of highest mold growth index_ 1% rain leakage

Figure 7: Probability density functions of highest mold growth index_ 0.5% rain leakage_ east

Figure 8: Probability density functions of highest mold growth index_ 0.1% rain leakage_ baseline wall_ east

509 **Table 1: Four categories of wall assemblies**

Wall types	Wall framing	Insulation	RSI K.m ² /W
Baseline wall	140 mm framing	140 mm fiber glass (with poly vapor barrier))	3.9
I-joist deep cavity wall	241 mm I-joist	241 mm cellulose fiber (with poly vapor barrier)	5.8
Exterior insulated wall	140 mm framing	140 mm fiber glass; 50 mm exterior polyisocyanurate insulation (without poly vapor barrier)	6.1
	140 mm framing	140 mm fiber glass; 76 mm exterior mineral wool insulation (with poly vapor barrier)	6.0

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527 **Table 2: Material properties of baseline wall, I-joist wall, and exterior insulated walls**

	ρ (kg/m ³)	θ_{por} (m ³ /m ³)	W_f (kg/m ³)	μ_{Dry} -	D_{ww} (m ² /s)	c (J/kg·K)	λ (W/m·K)
Cement Board	1130	0.479	152	905	2.16E-8	840	0.24
Air Gap	1.3	0.999	-	0.56	-	1000	0.13
Polyisocyanurate	33.57	0.99	19.17	1622	-	1470	0.023
Mineral wool	125	0.95	1.14	4.21	-	850	0.036
Water Resistive Barrier	400	0.001	0.9	328	-	1500	2.4
OSB	650	0.9	377	994	1.29E-10	1880	0.1
Cellulose fiber	68	0.95	500	1.86	-	2500	0.042
Fiberglass	30	0.99	208	1.35	-	840	0.036
6-mil Polyethylene	130	0.001	-	4E6	-	2300	2.3
Gypsum Board	625	0.706	430.625	172	3.47E-11	870	0.16

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Table 3: Boundary conditions

α_{in} (W/m ² ·K)	α_{ex} (W/m ² ·K)	β_{in} (s/m)	β_{ex} (s/m)	α_s -	α_l -	F_E -	F_D -
8	17	5.6E-8	1.19E-7	0.6	0.9	1.0	0.35

Table 4: Stochastic variables of hygric properties

OSB			Cellulose fiber		Fiberglass		Polyisocyanurate		Mineral wool	
W_f	μ_{Dry}	A	W_f	μ_{Dry}	W_f	μ_{Dry}	W_f	μ_{Dry}	W_f	μ_{Dry}
kg/m ³	-	kg/m ² ·s ^{0.5}	kg/m ³	-	kg/m ³	-	kg/m ³	-	kg/m ³	-
337	994	0.0022	500	1.86	208	1.35	19.7	1622	1.41	1.2
(54)	(38)	(0.00055)	(21)	(0.12)	(14.5)	(0.034)	(1.3)	(151)	(0.094)	(0.08)

Note: the values above the parentheses are mean values, those are in the parentheses are standard deviations

Table 5: Scenario variables and their combination with stochastic variables

Factor combination scenarios	Orientation	Rain Leakage position	Quantity of rain leakage	Stochastic variables
1	South	WRB	1% of wind-driven rain	Material properties and rain deposition factor
2	East	WRB		
3	South	Exterior surface of OSB		
4	East	Exterior surface of OSB		
5	South	Interior surface of OSB		
6	East	Interior surface of OSB		

605 **Table 6: The highest MCs and their uncertainties**

	Different rain leakage position_East			Different rain leakage position_South		
	WRB	Exterior of OSB	Interior of OSB	WRB	Exterior of OSB	Interior of OSB
Baseline wall	13 ± 5%	50 ± 22%	53 ± 27%	9 ± 4%	18 ± 10%	38.5 ± 26.5%
I-joist wall	12.5 ± 4.5%	38.6 ± 25%	45 ± 29%	11 ± 4%	14 ± 6%	33.5 ± 24.5%
Polyisocyanurate wall	10 ± 4%	34.5 ± 24%	42 ± 31%	8.5 ± 3.5%	10 ± 5%	31 ± 25%
Mineral wool wall	9 ± 3%	44.5 ± 39.5%	47 ± 28%	8 ± 3%	11 ± 6%	37 ± 25%

Table 7: Threshold of rain deposition factors_ 1% rain leakage_ East

Rain Leakage Position	Baseline wall	I-joist wall	Polyisocyanurate wall	Mineral wool wall
WRB	NR	NR	NR	NR
Exterior	0.35	0.35	0.65	0.35
Interior	0.35	0.35	0.65	0.35

Table 8: Threshold of rain deposition factors_1% rain leakage_ South

Rain Leakage Position	Baseline wall	I-joist wall	Polyisocyanurate wall	Mineral wool wall
WRB	NR	NR	NR	NR
Exterior	0.94	NR	NR	NR
Interior	0.48	0.7	NR	0.7

Table 9: Threshold of rain deposition factors_ 0.5% rain leakage_ East

Rain Leakage Position	Baseline wall	I-joist wall	Polyisocyanurate wall	Mineral wool wall
WRB	NR	NR	NR	NR
Exterior	0.35	0.78	NR	0.83
Interior	0.35	0.44	NR	0.36

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704 **Table 10: Threshold of rain deposition factors_ 0.1% rain leakage_ East**

Rain Leakage Position	Baseline wall	I-joist wall	Polyisocyanurate wall	Mineral wool wall
WRB	NR	NR	NR	NR
Exterior	NR	NR	NR	NR
Interior	0.85	NR	NR	NR

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Figure 1: Plan view of the tested walls (the figures are adapted from Fox (2014))

160x86mm (300 x 300 DPI)

Figure 2: Positions of rain leakage deposition
86x69mm (300 x 300 DPI)

Figure 3: Stochastic results of MC with variation of material properties and rain deposition factors (1% of wind-driven rain)_Rain Leakage on WRB

90x104mm (300 x 300 DPI)

Figure 4: Stochastic results of MC with variation of material properties and rain deposition factors (1% of wind-driven rain)_Rain Leakage on Exterior Surface of OSB

90x103mm (300 x 300 DPI)

Figure 5: Stochastic results of MC with variation of material properties and rain deposition factors (1% of wind-driven rain)_Rain Leakage on Interior Surface of OSB

90x104mm (300 x 300 DPI)

Figure 6: Probability density functions of highest mold growth index_ 1% rain leakage
121x106mm (300 x 300 DPI)

Figure 7: Probability density functions of highest mold growth index_ 0.5% rain leakage_ east

160x97mm (300 x 300 DPI)

Figure 8: Probability density functions of highest mold growth index_ 0.1% rain leakage_ baseline wall_ east
216x103mm (300 x 300 DPI)