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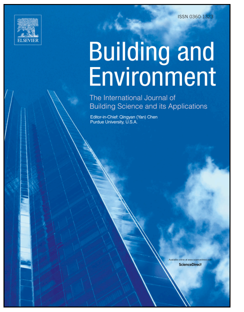

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Stochastic modelling of hygrothermal performance of highly insulated wood framed walls

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Abstract

As energy consumption has become an important issue in building design, most building codes require a higher insulation level for building envelopes to improve the building's energy efficiency. However, the highly insulated walls may lead to a higher risk of moisture problems. Although hygrothermal simulation has been widely used to investigate the moisture performance of wood framed walls, the uncertainties of input parameters such as material properties, boundary conditions and moisture loads, may lead to discrepancies between simulation results and actual performance of the envelope. This paper investigates the hygrothermal performance of highly insulated wood framed walls using a stochastic approach, which combines the Latin Hypercube Sampling method and Factorial Design to take into account the uncertainties of material properties, boundary conditions and moisture loads (air leakage and rain leakage). The investigated walls include an I-joist deep cavity wall, two exterior insulated walls, and a conventional 2x6 stud wall as the baseline. It is found that under the moisture loads introduced (i.e. air leakage and rain leakage), the exterior insulated walls have a lower mold growth risk than the deep cavity wall and the 2x6 stud baseline wall. The uncertainties of material properties do not result in significant variations in simulation results such as moisture content and mold growth index as uncertainties of moisture loads do. The hygrothermal performance of these highly insulated walls is more sensitive to moisture loads and the significance of the moisture loads (air leakage and rain leakage) depends on climatic conditions.

Keywords: *stochastic modeling, HAM simulations, hygrothermal performance, highly insulated wood framed walls, mold growth risk, durability*

Nomenclature

Symbol	**Parameter**	**Unit**
A	Water absorption coefficient	$kg/m^2 \cdot s^{0.5}$
c	Specific heat capacity of dry material	$J/kg \cdot K$
D_{ww}	Moisture diffusivity at saturation state	m^2/s
F_D	Rain deposition factor	-
F_E	Rain exposure factor	-
L_{cd}	Stud cavity depth starting from interior of OSB sheathing	m
q_{CL}	Air leakage flux	$m^3/m^2 \cdot s$
w_f	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	$W/m^2 \cdot K$
α_{in}	Interior heat transfer coefficient	$W/m^2 \cdot K$
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

Wood-frame construction is one of the main building types for residential buildings in North America because of their features such as light-weight, easily built and environmental friendly. However, prolonged exposure to moisture during construction and in service is a durability concern for wood framed envelopes. As energy consumption has become an important issue in building design, most of building codes require a higher insulation level for building envelopes to improve building's energy efficiency. There are different design strategies to achieve a higher insulation level of wood framed building envelopes, such as increasing the depth of stud cavity to accommodate thicker insulation or adding an exterior insulation while keeping the depth of stud cavity unchanged [1]. However, the highly insulated walls may lead to a higher risk of moisture problems. The deep cavity walls will reduce the temperature of the wood sheathing, which may increase the potential for condensation [2]. The exterior insulated walls may lower the drying capacity of the wood sheathing if the exterior insulation has a low vapour permeance [3].

Some research have been carried out to investigate the hygrothermal performance of highly insulated walls [4],[5],[6],[7],[8],[9],[10],[11],[12]. Pihelo et al. investigated the highly insulated wood framed walls with different cavity insulation through field measurement. It was found that the wall with cellulose insulation has lower mold growth risk than that with mineral wool insulation in cold climate zone [10]. Smegal et al. performed experimental study on exterior insulated wood framed walls with low-permeance exterior insulation (XPS) and high-permeance exterior insulation (mineral wool). They concluded that both low-permeance and high-permeance exterior insulation have no effect on durability performance, while the wall with high-permeance insulation dries more quickly after the water intrusion event [11]. Trainor et al. studied 2x6 stud cavity wall with fiberglass insulation, deep cavity wall with cellulose insulation and exterior insulated walls with fiberglass cavity insulation and different exterior insulations (mineral wool, XPS and polyisocyanurate) through field measurement and hygrothermal modelling. It was concluded that the exterior insulated walls are more moisture-durable than 2x6 stud wall and deep cavity wall under both normal operating condition and air leakage/rain leakage conditions. They recommended that the vapour resistance of interior vapour barrier should be reduced when the exterior insulation was installed to allow the moisture redistribute toward inside if necessary [12]. Although some design guidelines of highly insulated wood framed walls have been provided in previous studies, these studies were based on field measurement or hygrothermal modelling or the combination of these two, which did not consider the uncertainties of the factors that influence the hygrothermal performance. By field measurements, the hygrothermal performance of the investigated walls are monitored under a specific climatic condition. The hygrothermal models can be created and calibrated based on the field measurements, and simulations can be performed to evaluate the wall performance under other climatic conditions. Generally, the hygrothermal models are deterministic models, which use the deterministic values for the input parameters. However, factors influencing the hygrothermal responses are stochastic in nature such as the variability of material properties, boundary conditions, as well as the moisture loads. The uncertainties of input parameters may lead to a deviation between the simulation results and the actual performance of envelope assemblies, consequently, may lead to faulty designs.

Stochastic modelling has been used to investigate the uncertainties of input parameters and their influences [13],[14],[15],[16]. However, the stochastic parameters were only limited to material properties and boundary conditions in these studies without considering the moisture loads such as air leakage and rain leakage. Annex 55 conducted comprehensive researches to develop the probabilistic assessment methodology. More stochastic data about material properties, air leakage and internal moisture loads were collected [17], the stochastic modelling methods were thoroughly investigated [18], the risk management framework was established [19] and practical guidelines were provided [20]. In recent years, the probabilistic approach and stochastic methods have been increasingly applied to building hygrothermal performance evaluation [21],[22],[23],[24],[25],[26],[27]. Vereecken et al. applied Latin Hypercube Sampling method to investigate the energy savings and hygrothermal risks of internally insulated masonry wall. The probabilistic parameters investigated include climate conditions, boundary conditions, wall thickness and material properties, and indoor conditions. The impact of rain load was also analyzed, but the influence of rain penetration caused by the defect of the envelope was not explicitly discussed [24]. Marincioni et al. developed predictive models based on stochastic analysis to investigate moisture risks of internally insulated wall. The key influential parameters were identified by global sensitivity analysis and the statistical meta-models were formulated to establish the relationship between the key parameters and response variables. It was found that the orientation, rain exposure coefficient and effective saturation moisture content were the important parameters for mold growth index. The statistical predictive models can be used for fast moisture risk assessment for internal insulation retrofit [27]. Wang and Ge developed a stochastic modelling framework, which combines the Latin Hypercube Sampling method and Factorial Design to organize the stochastic material properties, boundary conditions and moisture loads. The developed methodology was applied to investigate the uncertainties of the hygrothermal performance of CLT wall assemblies, and the significance of the influential parameters under different levels of rain leakage, but the influence of the uncertainty of air leakage was not investigated [28]. In summary, the probabilistic approach and stochastic modelling methods are more frequently used to identify significant influential factors and assess moisture risks. However, few studies took into account the defect of the envelopes, and the impacts of air leakage and rain leakage have not been explicitly investigated. Additionally, the deep cavity walls and exterior insulated walls are the most commonly used highly insulated wood framed walls in North America, however, there is a lack of studies investigating their hygrothermal performance through the stochastic approach that takes into account the uncertainties of the influential factors.

This paper evaluates the hygrothermal performance of highly insulated wood frame walls using the stochastic modeling approach. The highly insulated walls investigated include an I-joist deep cavity wall with cellulose fiber cavity insulation, two exterior insulated walls with low and high vapour permeable insulation. A conventional 2x6 stud wall is also investigated to compare with the highly insulated walls. Moisture content and mold growth index are used as performance indicators for hygrothermal performance evaluation under different moisture loads (air leakage and rain leakage) in two climatic conditions- Waterloo (representing a cold climate zone) and Vancouver (representing a mild and humid climate zone).

2 Method

The stochastic modeling approach developed by Wang and Ge is applied to highly insulated wood framed walls [28]. The stochastic modeling of hygrothermal performance combines the Latin Hypercube Sampling method and Factorial Design. The influential parameters can be categorized into stochastic variables and scenario variables. The parameters that describe material properties can be considered as stochastic variables because every value falls into the range of the parameter that is possible to occur. The parameters that describe moisture load levels such as air leakage rate and rain leakage rate can be considered as stochastic variables as well. Standard stochastic analysis procedure can be performed to obtain the stochastic results of moisture content or mold growth index, which are used to evaluate the moisture damage risks. Regression sensitivity analysis can be performed to obtain the sensitivity indexes such as PCCs, which are used to evaluate the significance of the influence of material properties and moisture loads. However, the sensitivity indexes obtained from the regression analysis only reflect the significance of the correlation between input and output variables, but they cannot reflect how much uncertainty of the outputs is caused by a specific input variable. To evaluate the significance of moisture loads, it is necessary to know the increment of the results' uncertainty under a specific type of moisture load. Therefore, the type of moisture load is considered as scenario variable with only two states "happen" or "not happen", thereby the hygrothermal performance of the wood framed walls can be evaluated under different types of moisture loads.

The stochastic variables can be sampled by Latin Hypercube Sampling (LHS) method, and the scenario variables can be organized by Factorial Design to investigate all the possible combination of the variables at different states. Simulations are performed for the stochastic models generated by combining Latin Hypercube Sampling and Factorial Design to evaluate the moisture content level and mold growth risk of the walls under various moisture loads. The significance of the influential factors is evaluated by comparing the uncertainties of the simulation results under different scenarios. Fig.1 shows the stochastic modeling framework.

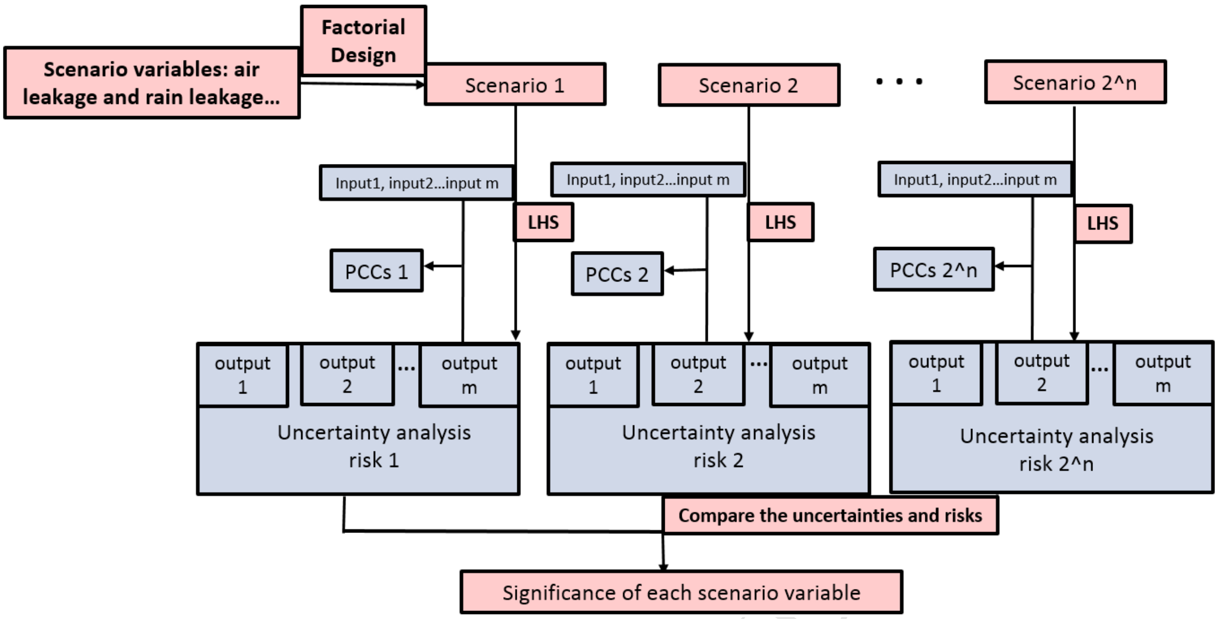


Fig.1. Stochastic modelling framework- a combination of LHS and Factorial Design

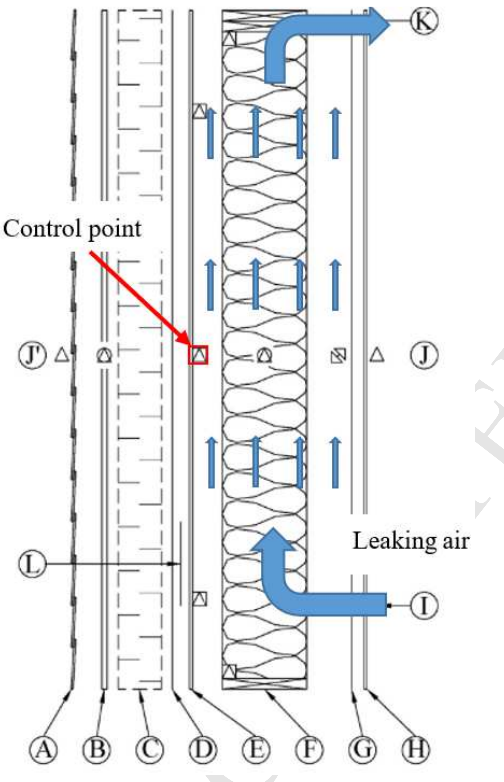
2.1 Hygrothermal models set up

DELPHIN, a simulation program for coupled heat, air and moisture transport in porous building materials, is used for the hygrothermal simulations. In this paper, the 1-D models are created and simulated using DELPHIN. 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. As one of the main moisture source, air leakage was simulated by injecting indoor air into the stud cavity. As shown in Fig. 2, for each wall, an air injection port was installed at the bottom of the interior drywall to provide a constant volume of indoor air (0.315 l/s) into the stud cavity for simulating the air leakage under natural condition (indoor and outdoor air pressure difference of 5Pa). The temperature, relative humidity and moisture content through the wall assemblies were monitored from Oct. 2012 to Jun. 2013, which was divided into baseline period (Oct. 2012 to Feb. 2013), air leakage period (Feb. 2013 to Apr. 2013) and drying period (Apr. 2013 to Jun. 2013). The base models of hygrothermal simulation are calibrated by comparing the simulation results with the measurements during the test period [29]. More details about the experimental set up can be found in [30].

Four of the test walls are selected for the stochastic modeling in this paper. They are I-joist wall and exterior insulated walls, and the conventional 2x6 baseline wall. Table 1 shows the details of the framing and insulation of the tested walls, and Fig. 2 shows the details of the wall components. The control point (the interior side of the OSB panel) is the point observed for performance evaluation.

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	3.9
I-joist deep cavity wall	241 mm I-joist	241 mm cellulose fiber	5.8
Exterior insulated wall	140 mm framing	140 mm fiber glass; 50 mm exterior polyisocyanurate insulation	6.1
	140 mm framing	140 mm fiber glass; 76 mm exterior mineral wool insulation	6.0



ID	**Wall component**
A	11 mm Fiber cement siding
B	19 mm strapping / drainage space
C	Exterior Insulation (polyisocyanurate or mineral wool)
D	SBPO air barrier and water resistive layer
E	11 mm OSB Sheathing
F	140, or 241 mm framing as required
G	6-mil polyethylene (polyisocyanurate wall has no poly)
H	12.5 mm drywall
I	Air injection port
J'-J	Sensors through wall insulation cavity
K	Air exhaust port
L	Exterior water injection wetting sheet

Fig. 2. General section view of the highly insulated walls and the wall components (adapted from Fox, 2014 [30])

The hygrothermal models of the investigated walls were created in DELPHIN using the mean values of the material properties and monitored indoor and outdoor climatic conditions. The hygrothermal models are validated by comparing the simulation results with the measurements [29], [30]. Table 2 and Table 3 show the material properties and boundary conditions of the base models.

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

	ρ (kg/m³)	$θ_{por}$ (m³/m³)	W_f (kg/m³)	$μ_{Dry}$ -	D_{ww} (m²/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
Gypsum Board	625	0.706	430.625	172	3.47E-11	870	0.16

Table 3 Boundary conditions

$α_{in}$ (W/m²·K)	$α_{ex}$ (W/m²·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

The wind-driven rain is calculated based on the semi-empirical model in ASHRAE 160-2016 [31]. The rain leakage is simulated by depositing a 1% of wind-driven rain on the exterior surface of the OSB sheathing.

Although DELPHIN has the built-in air balance equation, the convective air flow is considered separately from heat and moisture transport [32]. To model the air leakage effect on OSB, a source term (heat or moisture source), which reflects the amount of the heat or moisture carried by the leaking air, is integrated into the heat and moisture balance equations. There are two simplified methods to simulate air leakage, air infiltration method and air convention method. The air infiltration method is to add a moisture source, which is equivalent to the condensation rate on the interior surface of OSB sheathing. The air convection method is to add a 1mm air layer, which is ventilated by indoor air, in the stud cavity. Then, the amount of the heat and moisture added in the stud cavity is calculated based on the indoor temperature, water vapour content and air exchange rate [33]. These two methods in hygrothermal modeling have been investigated by Wang and Ge and calibrated with measurements [29]. The air leakage rate is determined based on the air flow rate provided by the air injection port, a constant air flow rate of 0.315 L/s.m^{2}under 5 Pa indoor and outdoor air pressure difference, which reflects an average air leakage level under natural conditions without an elevated stack effect or high wind velocity according to ASHRAE Fundamental 2013 [34].For the air infiltration method, the total amount of air leakage is reduced by multiplying a percentage to reflect the actual amount of air reaching the OSB sheathing (as shown by the arrows close to the OSB panel in Fig.2). For the air convection method, the location of the 1mm air layer should be able to reflect cavity depth that the leaking air can reach. The actual amount of air reaching OSB and the position of the 1mm air layer are calibrated by comparing the simulated moisture content of OSB with that obtained from field measurements. It was found that the air infiltration method generally gives higher moisture content level than the air convection method for the baseline wall and I-joist wall. For polyisocyanurate exterior insulated wall, the air convection method is used as there is no condensation caused by the leaking indoor air using the air infiltration method.

In this paper, for the baseline wall and I-joist wall, air infiltration method is used because these walls have significant condensation potential caused by air leakage. The air convection method is used for exterior insulated walls when there is no condensation caused by air leakage or the condensation is not significant. The choice of air leakage modelling method (air infiltration method or air convection method) depends on the moisture content level obtained from these two methods. The method that obtains a higher moisture content level, representing a worse case, is used to simulate the impact of air leakage. The calibrated models are used as the base models for stochastic modelling.

2.2 Stochastic models set up

2.2.1 Stochastic variables

The hygric properties of OSB and insulation including saturation water content, vapour resistance factor at dry state and water absorption coefficient, are considered as stochastic variables. These variables are assumed to follow normal distribution. The mean values and standard deviations are obtained from Kumaran et al. and Mukhopadhyaya et al. [35], [36]. The stochastic variables of the hygric properties are listed in Table 4. The material property functions are scaled by multiplying coefficients: parameter_stochastic/parameter_mean.

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 (54)	994 (38)	0.0022 (0.00055)	500 (21)	1.86 (0.12)	208 (14.5)	1.35 (0.034)	19.7 (1.3)	1622 (151)	1.41 (0.094)	1.2 (0.08)

The surface transfer coefficients are considered as deterministic parameters since these parameters have no significant influence on the hygrohtermal performance of wood framed walls [15]. The rain deposition factor is considered as stochastic variable, which ranges from 0.35 to 1 and follows a uniform distribution, to reflect the variability of rain leakage. The air leakage rate (5.0 ± 3.7 m^3/h·m^2 under 75Pa pressure difference for walls with air barrier) is assumed to follow normal distribution according to the air leakage database developed by Emmerich and Persily [37], and converted to those under 5Pa pressure difference.

2.2.2 Scenario variables

The orientation, air leakage and rain leakage are considered as scenario variables. Table 5 shows the states of the scenario variables and their combinations with stochastic variables. To observe the impact of building enclosure itself and different types of moisture loads separately, the scenarios can be categorized into four groups: 1) Scenario1 and Scenario 2, which have no air leakage and rain leakage but only material properties are considered as stochastic variables. 2) Scenarios 3 and Scenario 4, with air leakage but without rain leakage. In this group, the material properties and air leakage rate are considered as stochastic variables. 3) Scenario 5 and Scenario 6, with rain leakage but without air leakage. The material properties and rain deposition factor are considered as stochastic variables. 4) Scenario 7 and Scenario 8, both air leakage and rain leakage are introduced. As for interior moisture load, two levels are specified.

The indoor condition created in field measurement is close to the lowest moisture load level calculated according to ASHRAE 160 [31], therefore, it is used as a lower level of internal moisture load. The higher level of internal load is obtained from the scenario with 4 bedrooms and 5 occupants according to ASHRAE 160 [31].

The material properties, air leakage rate and rain deposition factor are considered as stochastic variables. For each scenario, 100 stochastic models are generated by Latin Hypercube Sampling. Simulations are performed for five years starting from Oct. 2012. For Waterloo, the monitored one year weather data is repeatedly used for five-year simulation as a typical year. For Vancouver, the weather data from Canadian Weather Year for Energy Calculation (CWEC) is used for five-year simulation. The moisture content level and mold growth index at the interior surface of OSB sheathing is used for performance evaluation (as shown in Fig. 2: the control point). The stochastic simulations are performed using a hygrothermal simulation program-DELPHIN and a programming platform-MATLAB.

Table 5 Factorial design of scenario variables of highly insulated wood framed walls

Factor combination scenarios	**Orientation**	**Rain Leakage**	**Air Leakage**	**Stochastic variables**
1	North	Without (0%)	0	Material properties
2	South	Without (0%)	0	Material properties
3	North	Without (0%)	5.0$\pm$ 3.7 $m^3/h{\cdot}m^2$	Material properties and air leakage rate
4	South	Without (0%)	5.0$\pm$ 3.7 $m^3/h{\cdot}m^2$	Material properties and air leakage rate
5	North	With (1%)	0	Material properties and rain deposition factor
6	South	With (1%)	0	Material properties and rain deposition factor
7	North	With (1%)	5.0$\pm$ 3.7 $m^3/h{\cdot}m^2$	Material properties, air

				leakage rate and rain deposition factor
8	South or East	With (1%)	5.0$\pm$ 3.7 $m^3/h\cdot m^2$	Material properties, air leakage rate and rain deposition factor

3 Results and discussion

3.1 Stochastic analysis for Waterloo

3.1.1 Stochastic moisture content

Scenario group 1: Stochastic material properties

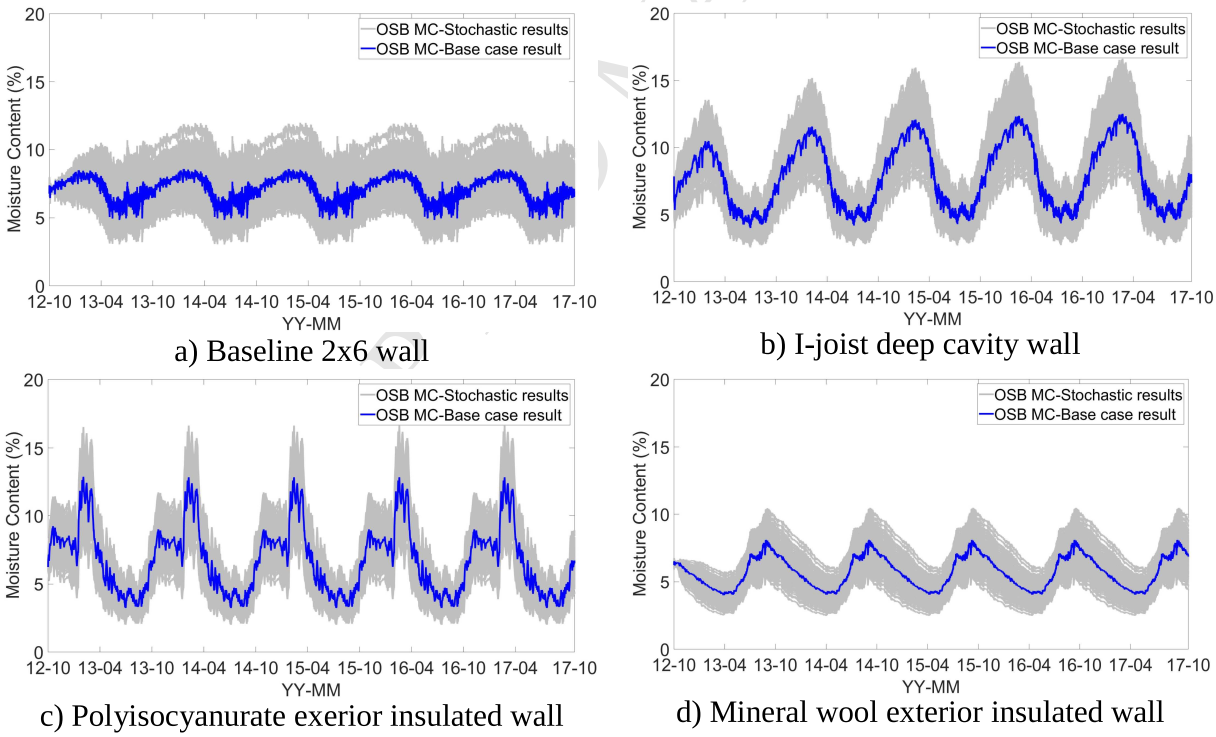


Fig. 3. Stochastic results of OSB MC with variation of material properties for north-oriented walls in Waterloo

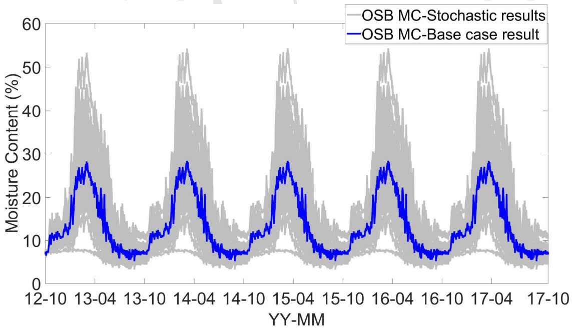
Fig. 3 shows the stochastic results of OSB moisture content with only the material properties are treated as stochastic variables. The blue curve is the result of the base case, which uses the mean values presented in Table 2 as the input parameters. The grey curves are the stochastic results with hygric properties listed in Table 4 being considered as stochastic variables and other parameters fixed. The moisture contents of south-oriented walls are similar to that of north-oriented walls (similar pattern but slightly lower MC level, within 2%), therefore, only the results of north-oriented walls are presented.

The highly insulated walls generally have higher MC level and more significant seasonal variation (increasing in winter and decreasing in summer) than the baseline wall except for mineral wool exterior insulated wall, which has similar MC level to the baseline wall but different seasonal variations (increasing from spring to summer but decreasing starting from fall to winter). For I-joist wall, the thicker insulation results in lower OSB temperature and higher OSB surface RH and a 4% higher MC compared to the baseline wall, while for polyisocyanurate insulated wall, although the OSB surface temperature is elevated due to its exterior insulation, its low vapour permeability restricts the vapour diffusion, therefore, results in higher MC at OSB sheathing during the wintertime. The high vapour permeability of mineral wool allows inward vapour diffusion from outdoor to OSB, therefore, there is an increase of moisture content of OSB during spring and summer time.

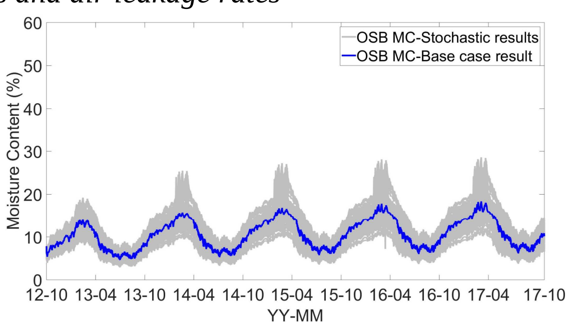
For the baseline wall, the moisture content of base case fluctuates seasonally between 5% and 8%. The uncertainty is about $\pm$3% throughout the five-year simulation period, with the highest MC of the extreme case is about 11%. For the I-joist wall, the moisture content of base case gradually increases with a seasonal fluctuation in the first three years. The annual peak value of moisture content increases from 10% in the first year to 12% in the third year, and becomes stable after the third year. The uncertainties of MC are about $\pm$ 2% in summer time and $\pm$4% in wintertime. The highest moisture content level of the extreme case is about 16%, which will not result in mold growth or other moisture problems.

The hygrothermal performance of polyisocyanurate exterior insulated wall is similar to the I-joist wall, except that the polyisocyanurate wall has no annual increase of MC. For mineral wool exterior insulated wall, the moisture content level and its seasonal variation are lower than polyisocyanurate exterior insulated wall. The MC of base case varies between 4% and 8%, with uncertainties about $\pm$1.5% in summer time and $\pm$2.5% in winter time, and the highest MC of the extreme case is about 10%. The mineral wool wall performs better than the polyisocyanurate wall because it has higher exterior permeance so that the moisture is easier to dry outward.

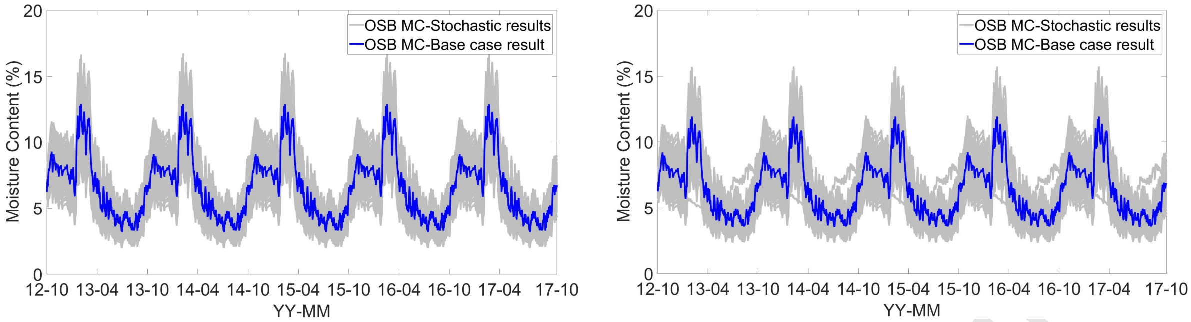
Scenario group 2: Stochastic material properties and air leakage rates



a) Baseline 2x6 wall



b) I-joist deep cavity wall



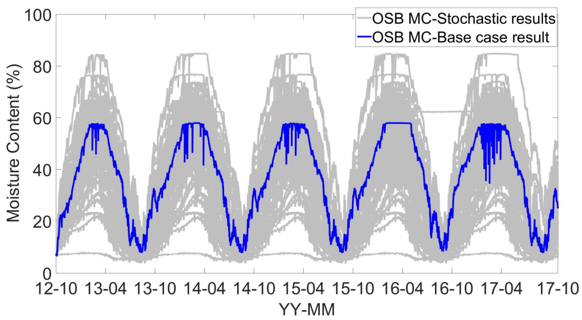
c) Polyisocyanurate exterior insulated wall d) Mineral wool exterior insulated wall

Fig. 4. Stochastic results of OSB MC with variation of material properties and air leakage rates at low internal moisture load for north-oriented walls in Waterloo.

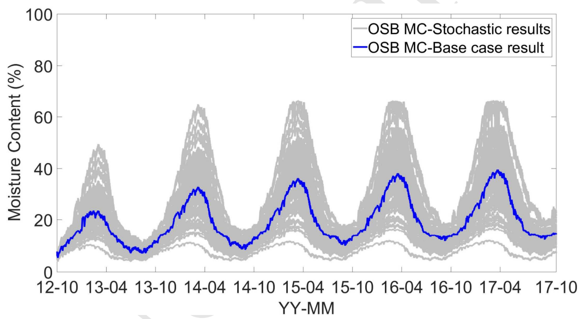
Fig. 4 shows the simulation results with air leakage under low internal moisture load, which has RH from 20% to 40%. When the air leakage is taken into account, the seasonal variation of MC of the baseline wall is much more significant than the scenario without air leakage. The average value of moisture content fluctuates between 8% and 30%, with uncertainties from ±4% in summer time to ±23% in winter time. The highest moisture content of the extreme case is about 53%.

The I-joist wall has a lower moisture content level than the baseline wall. The moisture content varies from 4% to 20% with uncertainties from ±2.5% to ±8%. The highest moisture content level of the extreme case is about 28%. The I-joist wall performs better than the baseline wall because the cellulose fiber in I-joist wall has a higher moisture storage capacity than fiberglass in the baseline wall, and the cellulose fiber is able to absorb the moisture carried by the air leakage and reduces the amount of moisture reached the OSB sheathing. The two exterior insulated walls have similar MC level and variation pattern in OSB, and the MC of OSB in polyisocyanurate wall is slightly higher than that in the mineral wool wall but both maintain below 20%, the risky level. For the polyisocyanurate wall, the moisture content of OSB sheathing fluctuates between 3% and 13% with an uncertainty of ±4%. The moisture content of OSB sheathing in the mineral wool wall fluctuates between 3% and 12% with the same uncertainty as the polyisocyanurate wall.

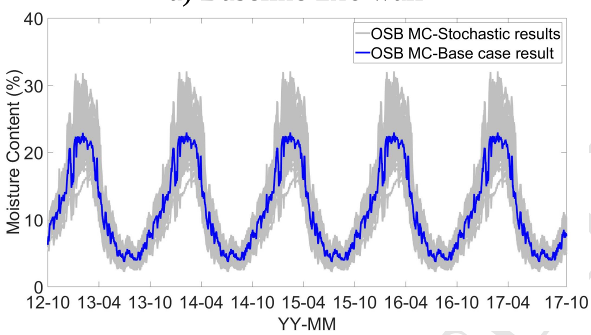
There is no condensation caused by air leakage for the exterior insulated walls, therefore, the OSB MC profiles obtained by air infiltration method are the same as those presented in Fig. 3 c, d. However, the air leakage still has an impact on the MC of OSB through vapour convection, therefore, air convection method is used to simulate the air leakage in the exterior insulated walls. For the polyisocyanurate wall and mineral wool wall, a 1 mm air layer with air change rate 840 1/h is placed in the 75%Lcd, which is the depth of the stud cavity from interior of OSB to the exterior of the gypsum board (polyisocyanurate wall) or vapour barrier (mineral wool wall), to simulate the impact of air leakage. The air change rate is considered as stochastic variables according to the variation of the air leakage rate listed in Table 5. Fig. 4 c, d are the stochastic results of exterior insulated walls using air convection method to simulate the air leakage. It can be seen from Fig. 4 c that the results of polyisocyanurate are similar to those without air leakage (Fig. 3 c) because polyisocyanurate wall has no vapour barrier and the influence of indoor air for the models without 1 mm air layer is comparable with those with 1 mm air layer. For the mineral wool wall, the results from the models with 1 mm air layer simulating air leakage (Fig. 4 d) is significantly different from those without air leakage (Fig. 3 d) because of the presence of vapour barrier. It can be seen that the stochastic results with 1 mm air layer simulating air leakage are higher than those without air leakage and the variation pattern is similar to the polyisocyanurate wall. The introduction of air leakage significantly increased the moisture load on the OSB sheathing in the mineral wool wall because the presence of vapour barrier minimizes the vapour diffusion without air leakage.



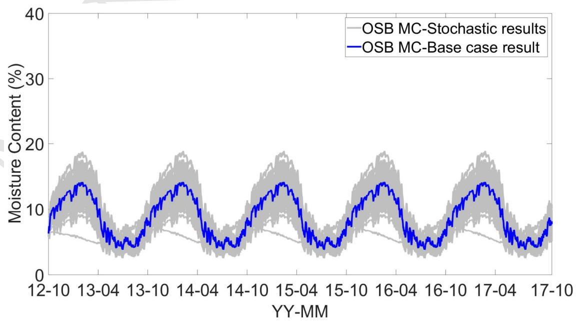
a) Baseline 2x6 wall



b) I-joist deep cavity wall



c) Polyisocyanurate exterior insulated wall



d) Mineral wool exterior insulated wall

Fig. 5. Stochastic results of OSB MC with variation of material properties and air leakage rates at high internal moisture load for north-oriented walls in Waterloo

Fig. 5 shows the stochastic results with air leakage at high internal moisture load, under which the RH fluctuates between 30% and 50%. It can be seen that the MCs of OSB and their uncertainties are much higher than the cases with air leakage under low internal moisture load. The baseline 2x6 wall has the highest MC increment, while the mineral wool wall has the lowest MC increment. The MCs variation pattern is similar to that under low internal moisture load.

For the baseline wall, the maximum MC is 82%, which is higher than that of the I-joist wall (66%). For the polyisocyanurate wall under high internal moisture load, air infiltration method is used to simulate the influence of air leakage because the moisture brought by condensation is much more than that brought by vapour convection. The maximum MC is 32%, which is lower than those of the baseline wall and the I-joist wall. Although there is also condensation potential for mineral wool wall under high internal moisture load condition, the maximum condensation moisture by air infiltration method is less than those brought by vapour convection, therefore, air convection method is used to simulate air leakage for the mineral wool wall. The maximum MC of OSB in the mineral wool wall is about 17%, which is much lower than that in the polyisocyanurate wall. The mineral wool insulated exterior wall can handle the high level of air leakage and has MC level below 20%, while the polyisocyanurate insulated walls has MC of OSB reaches as high as 30%, greater moisture risks than the mineral wool insulated wall, due to the low vapour permeability of polyisocyanurate. With polyethylene vapour barrier removed from the interior side, OSB can be dried towards interior, but only when inward vapour drive potential exists, which is in the spring and summer time, therefore, results in much higher MC in OSB during the winter time compared to the mineral wool exterior insulated walls.

Scenario group 3: Stochastic material properties and rain deposition factors

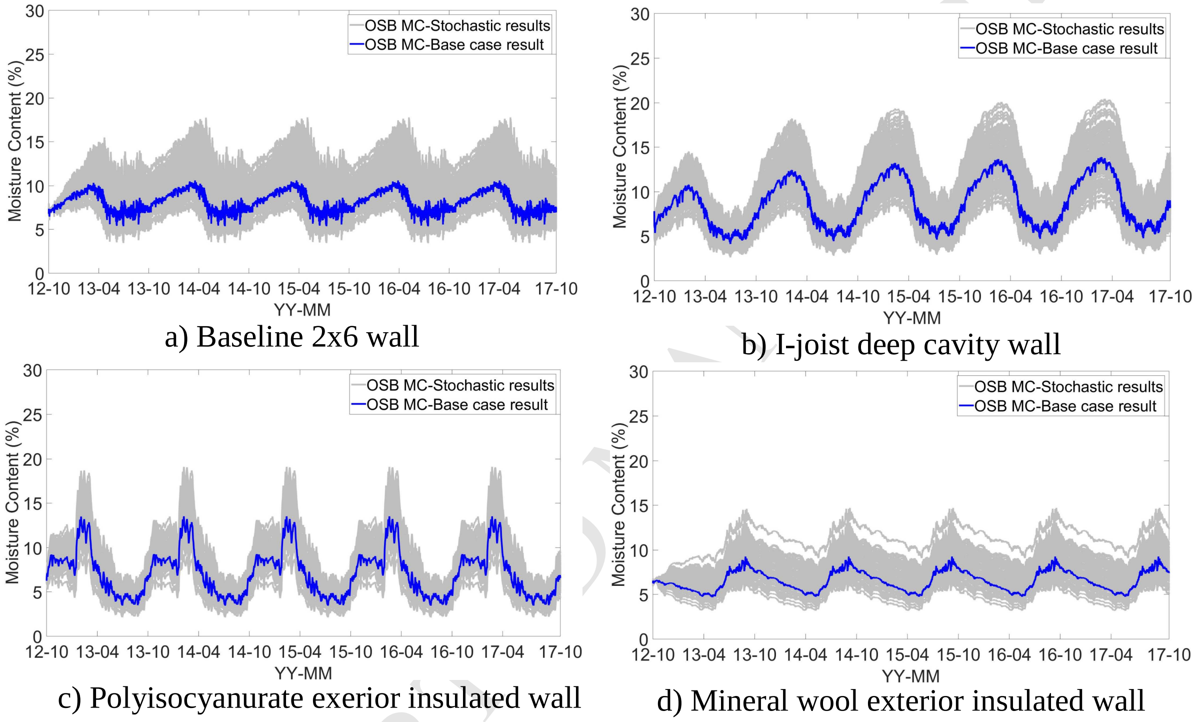


Fig. 6. Stochastic results of OSB MC with variation of material properties and rain leakage for south-oriented walls in Waterloo

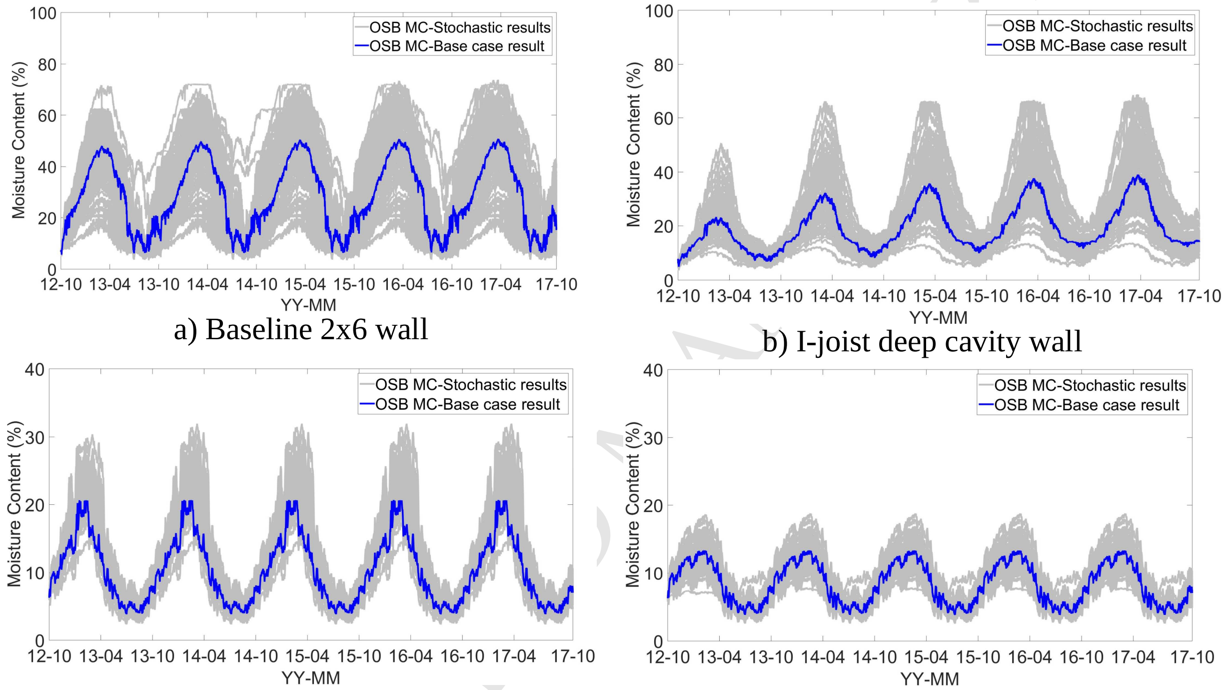
Fig. 6 shows the stochastic moisture content of the baseline wall and highly insulated walls with 1% wind-driven rain penetration. The rain leakage has a slight influence on the north-oriented walls with only a small increase of MC in OSB sheathing. The impact of rain leakage is more significant on the south-oriented walls because of the higher amount of wind-driven rain received on the south façade (158 mm on south facade, and 35 mm on north facade), therefore, only the results for south orientation are presented.

The south-orientated baseline wall has the MC uncertainties from $\pm$3% in summer time to $\pm$5% in winter time, with the highest value of the extreme case is about 17%. The MC level and their uncertainties are lower than the scenario with air leakage, which means the impact of rain leakage is less significant than air leakage. Similar observation can be found in south-orientated I-joist wall, which has moisture content level from 4% to 15%, with an uncertainty from $\pm$3% to $\pm$5%.

For the exterior insulated walls, the impact of rain leakage is slightly more significant than the air leakage at low internal moisture load because the moisture brought by rain leakage is higher than air leakage. The moisture content level of OSB in the south-oriented polyisocyanurate wall is from 5% to 14% with an uncertainty from ±2% to ±4%. The moisture content of OSB in the south-oriented mineral wool wall is lower than that in the polyisocyanurate wall due to its higher exterior vapour permeance.

In general, all the walls can handle the 1% rain leakage with MCs of OSB remaining below 20% in spite of the slight difference among these walls.

Scenario group 4: Stochastic material properties, air leakage rates and rain deposition factors



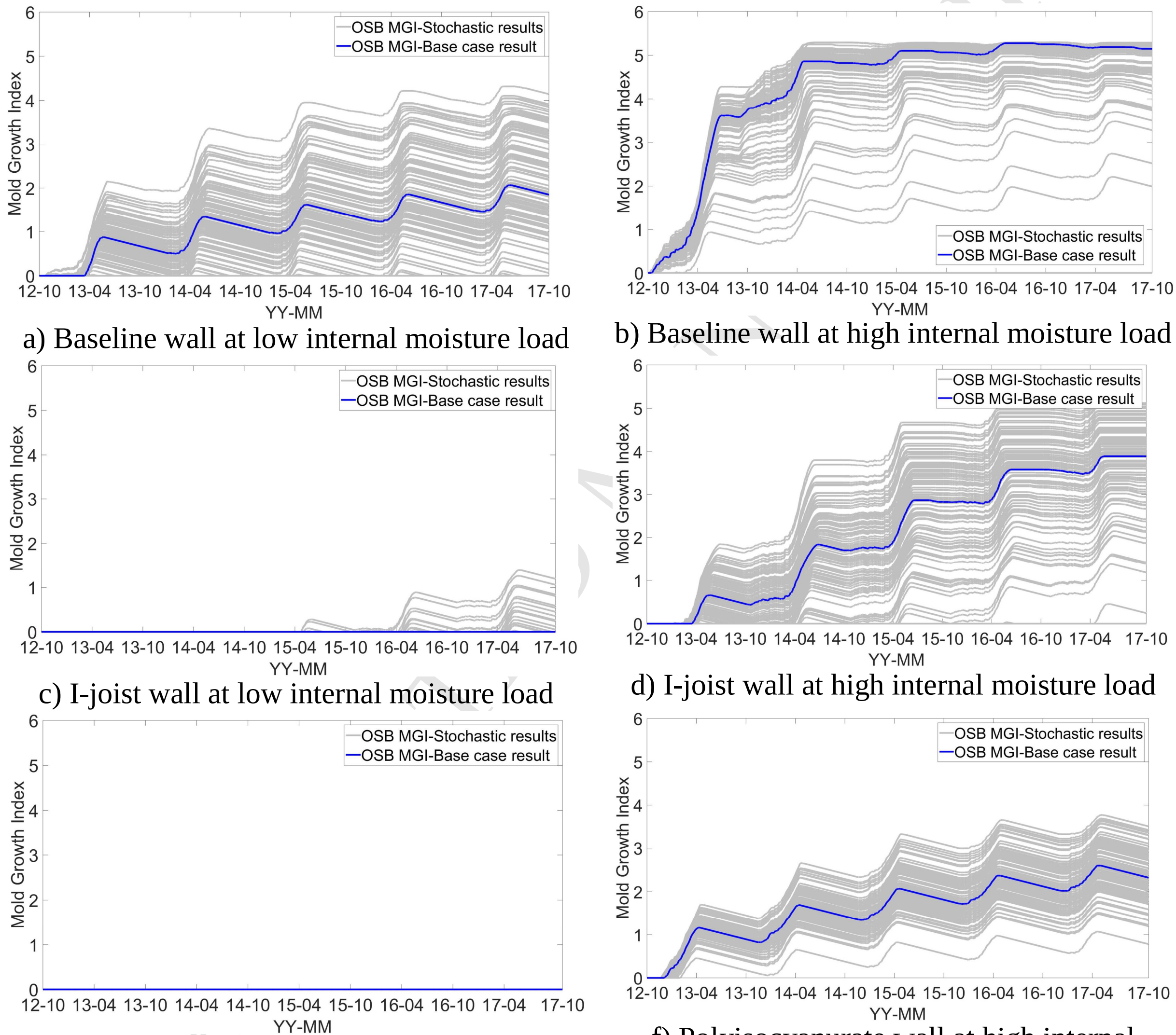
a) Baseline 2x6 wall   b) I-joist deep cavity wall

c) Polyisocyanurate exterior insulated wall   d) Mineral wool exterior insulated wall

Fig. 7 Stochastic results of OSB MC with variation of material properties, air leakage rates (high internal moisture load) and rain leakage for south-oriented walls in Waterloo

For scenario group 4, simulations are performed only for south orientation because of the insignificant influence of rain leakage for north orientation. The air leakage at high internal moisture load is combined with the rain leakage for south orientation. The moisture content levels in OSB are slightly lower than that in the north-oriented walls simulated with air leakage at high internal moisture load only (compared to Fig. 5). The baseline wall is the worst followed by the I-joist wall and the polyisocyanurate insulated wall. The mineral wool exterior insulated wall performs the best with MC levels in OSB remaining below 20%. For the climatic condition of Waterloo, air leakage has a greater impact than rain leakage and to have moisture safe highly insulated walls, air leakage rate needs to be controlled to a low level. In general, exterior insulated walls are safer than deep cavity and conventional 2x6 walls.

3.1.2 Mold growth risk analysis



a) Baseline wall at low internal moisture load
b) Baseline wall at high internal moisture load
c) I-joist wall at low internal moisture load
d) I-joist wall at high internal moisture load
e) Polyisocyanurate wall at low internal moisture load
f) Polyisocyanurate wall at high internal moisture load

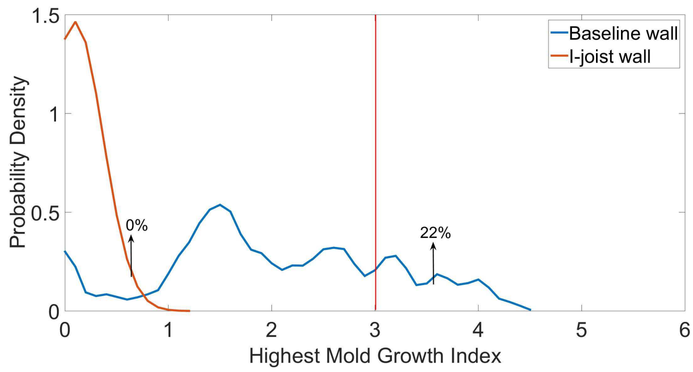
Fig. 8. Mold growth index (MGI) on OSB sheathing with air leakage for north-oriented walls in Waterloo

Fig. 8 shows the mold growth index, which is calculated based on the model developed by Ojanen et al. [38], for north-oriented walls with air leakage at low and high internal moisture loads. The mold growth index on OSB sheathing for the mineral wool exterior insulated wall is zero under both low and high internal moisture load conditions, therefore, the results for the exterior insulated mineral wool wall is not presented.

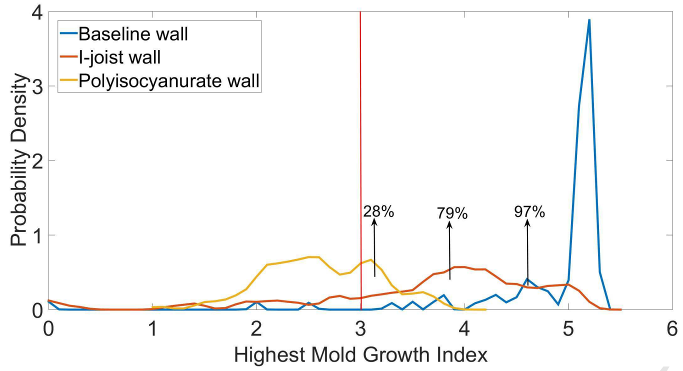
For the baseline wall with air leakage at low internal moisture load, the mold growth index of base case is in the middle of the stochastic cases, and increases with a seasonal variation (decreasing in summer time and increasing in winter time) from 0 in the first year to 2 in the fifth year. The stochastic cases are evenly distributed around the base case, with a highest value of 4.3 of the extreme case in the fifth year. Under high internal moisture load, the mold growth index of the base case increases steeply in the first two years up to 5, which indicates a considerable amount of mold growth on OSB sheathing surface. The stochastic cases are evenly distributed around the base case in the beginning stage (from Oct. 2012 to Apr. 2013), while dispersed from Oct. 2013. Most cases are increasing steeply with the same rate as the base case, while a few cases increase slowly and become much lower than the base case. At the end of the fifth year, most of the stochastic cases are congregated above 4, and a few cases are distributed sparsely between 2 and 4.

For the I-joist wall with air leakage at low internal moisture load, the mold growth indexes are zero in the first two years. Only a few cases have the mold growth index higher than zero from Apr. 2015, with a maximum value of 1.4 in the fifth year, which indicates no mold growth risk. For the scenario with air leakage at high internal moisture load, the mold growth index of the base case increases from zero in the first year to 3.9 in the fifth year, and slightly higher than the average level of the stochastic cases. The stochastic cases above average are more crowded than those below the average, the highest mold growth index in the fifth year is 5.1.

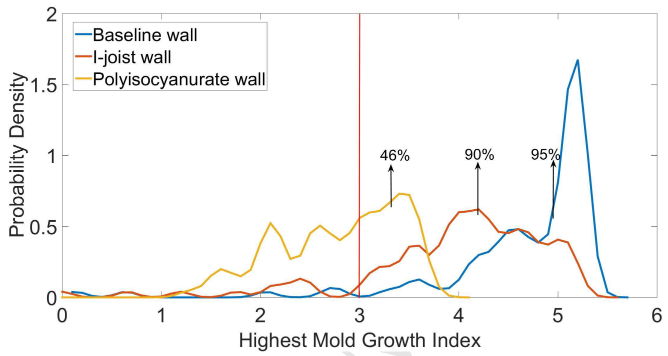
For the polyisocyanurate wall with air leakage at the low internal moisture load, the mold growth index is zero throughout the five years. Under high internal moisture load, the mold growth index of the base case increases from zero in the first year to 2.6 in the fifth year with a seasonal variation (decreasing in summer time and increasing in winter time). The stochastic cases are evenly distributed around the base case with a highest mold growth index of 3.7 in the fifth year.



a) With air leakage at low internal moisture load: north



b) With air leakage at high internal moisture load: north



c) With air leakage at high internal moisture load and rain leakage: south

Fig. 9. Probability density functions of the highest mold growth index at the end of the fifth year simulated with air leakage and rain leakage in Waterloo

Fig. 9 shows the probability density function of the highest mold growth index for the baseline wall, I-joist wall and polyisocyanurate wall under different scenarios. According to ASHRAE 160-2016 [31], the mold growth index of the building components surface should not exceed 3 to avoid mold growth problem, therefore, the mold growth risk can be defined as the probability that the highest mold growth index exceeding 3. It can be seen that the north-oriented baseline wall has the highest mold growth risk among the three types of walls. For the scenario with air leakage at low internal moisture load, there are 22% of stochastic cases for the baseline wall that have the highest mold growth index higher than 3, which is a threshold of visually detectable mold growth on the surface. But the mold growth risk is zero for the north-oriented I-joist wall and the polyisocyanurate exterior insulated wall. For the scenarios with air leakage at high internal moisture load condition, the north-oriented baseline wall has 97% stochastic cases that have the highest mold growth index higher than 3. The probability is 79% for the north-oriented I-joist wall, and 28% for the north-oriented polyisocyanurate wall. For the scenario with air leakage at high internal moisture load and rain leakage, the mold growth risks for the south-oriented baseline wall is slightly lower (95% v.s. 97%) than the scenario with only air leakage at high internal moisture load for the north-oriented baseline wall, while the south-oriented I-joist wall and polyisocyanurate wall have higher mold growth risks than the north-oriented walls with air leakage at high internal moisture load only.

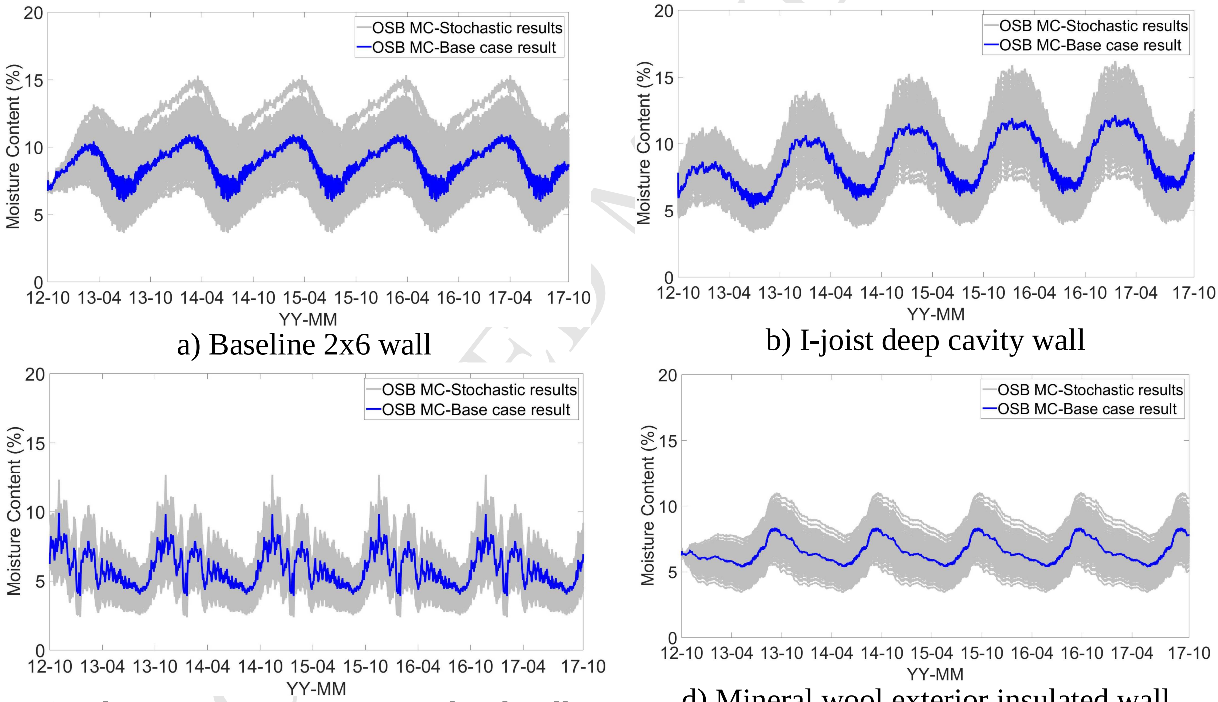
3.2 Stochastic analysis for Vancouver

3.2.1 Stochastic results of moisture content

Scenario group 1: stochastic material properties

Fig. 10 shows that the moisture content patterns of the walls in Vancouver are similar to those in Waterloo when there are no air leakage or/and rain leakage. The MCs of OSB remains below 15%.

For the baseline wall and I-joist wall, the uncertainty of the moisture content in Vancouver (Fig. 10) is slightly higher than in Waterloo (Fig. 3) (4% v.s. 3%). For the exterior insulated walls, the MC of polyisocyanurate wall in Vancouver is slightly lower than that in Waterloo (3% v.s. 4%), while the mineral wool wall has similar MC to that in Waterloo.



a) Baseline 2x6 wall

b) I-joist deep cavity wall

c) Polyisocyanurate exterior insulated wall

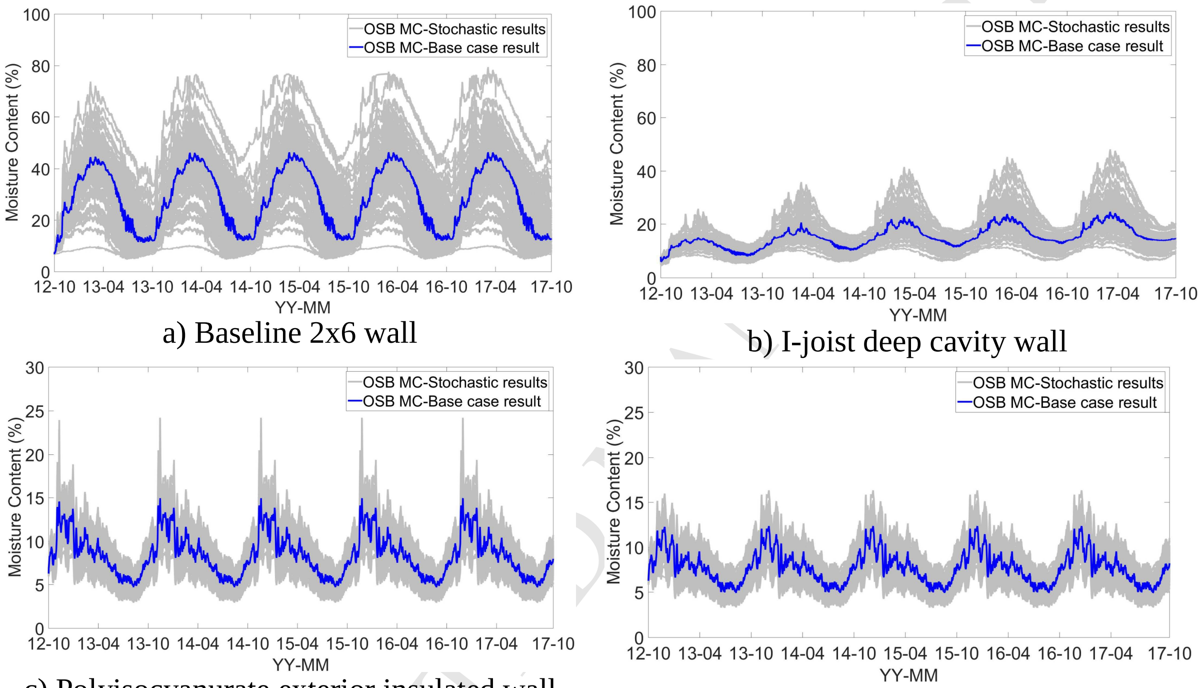
d) Mineral wool exterior insulated wall

Fig. 10. Stochastic results of OSB MC with variation of material properties for north-oriented walls in Vancouver

Scenario group 2: stochastic material properties and air leakage rates

For the scenarios with air leakage at low internal moisture load condition, the air leakage does not result in MC in OSB exceeding 20%, no mold growth risk, therefore, the stochastic results for these scenarios are not presented. As shown in Fig. 11, under the high internal moisture load condition (RH30% to RH50%), the MC level of OSB sheathing is lower than that with air leakage at the high internal moisture load condition in Waterloo. The MC levels and variation of

OSB in the I-joist wall are less than that in the baseline wall because the cellulose fiber is able to absorb the moisture carried by leaking air, therefore, reduces the MC level of OSB. For the exterior insulated walls, the MC levels and variation of OSB in the polyisocyanurate wall are greater than that in the mineral wool wall, due to the low vapour permeability of polyiscyanurate, therefore, reduced drying toward outdoors. Air convection method is used to simulate air leakage for mineral wool exterior insulated walls given that higher MC levels, worse situation, is obtained by air convection method. Air infiltration method is used for the polyisocyanurate wall because the simulated moisture content level is higher by air infiltration method than by air convection method.



a) Baseline 2x6 wall

b) I-joist deep cavity wall

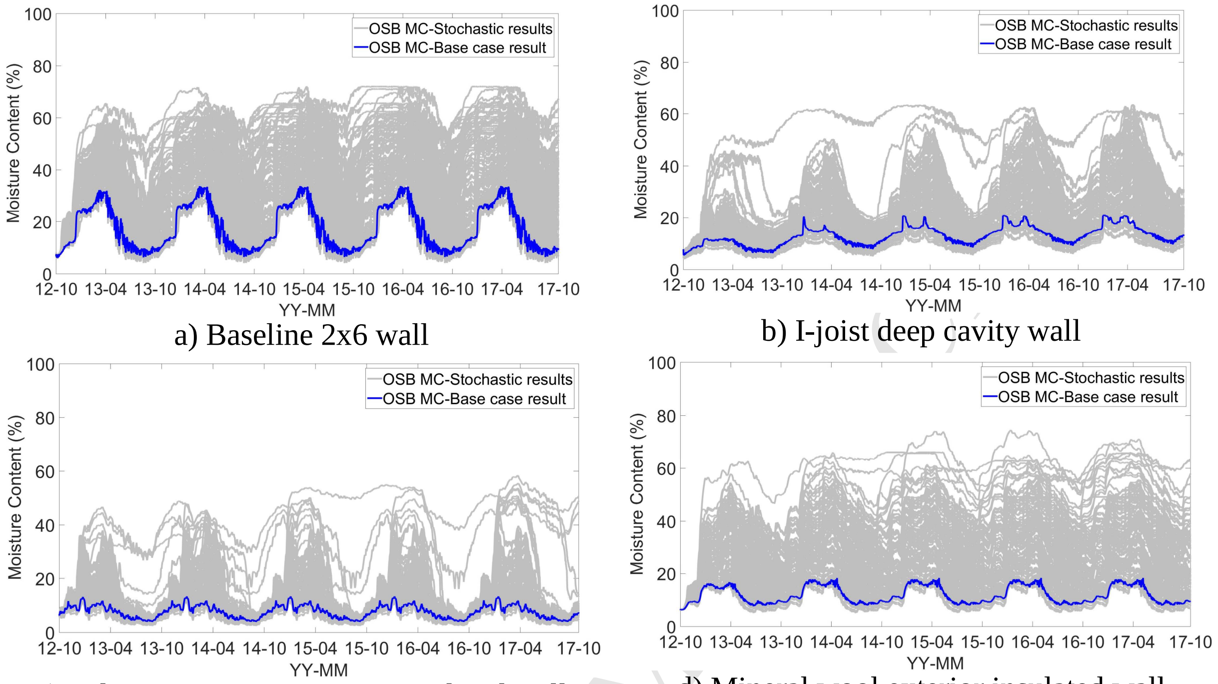
c) Polyisocyanurate exterior insulated wall

d) Mineral wool exterior insulated wall

Fig. 11. Stochastic results of OSB MC with variation of material properties and air leakage rate at high internal moisture load for north-oriented walls in Vancouver

Scenario grope 3: Stochastic material properties and rain deposition factors

For the rain leakage scenario, the simulations are performed for the east orientation instead of south orientation because the east orientation receives the highest amount of wind-driven rain in Vancouver. The results of north orientation are not presented since the north orientation receives the least amount of wind-driven rain. As shown in Fig. 12, for the east-oriented walls the base cases have almost the lowest moisture content level as they have the lowest rain deposition factor (0.35), which indicates rain deposition factor dominates the moisture content level for the east walls with 1% rain leakage. The baseline wall has higher MC level and uncertainties than the I-joist wall because the moisture storage capacity of fiberglass is lower than cellulose fiber. For the exterior insulated walls, the mineral wool exterior insulated wall has higher MC level and uncertainties than the polyisocyanurate exterior insulated wall because the vapour barrier of mineral wool wall impedes the inward transport of the moisture brought by rain leakage, while the moisture can be dried inward for the polyisocyanurate wall without vapour barrier. For the cases with 1% rain leakage assumed, the moisture content levels are generally higher than that in south facing walls in Waterloo because of the much higher amount of wind-driven rain (605 mm on east façade, and 56 mm on north facade).



a) Baseline 2x6 wall

b) I-joist deep cavity wall

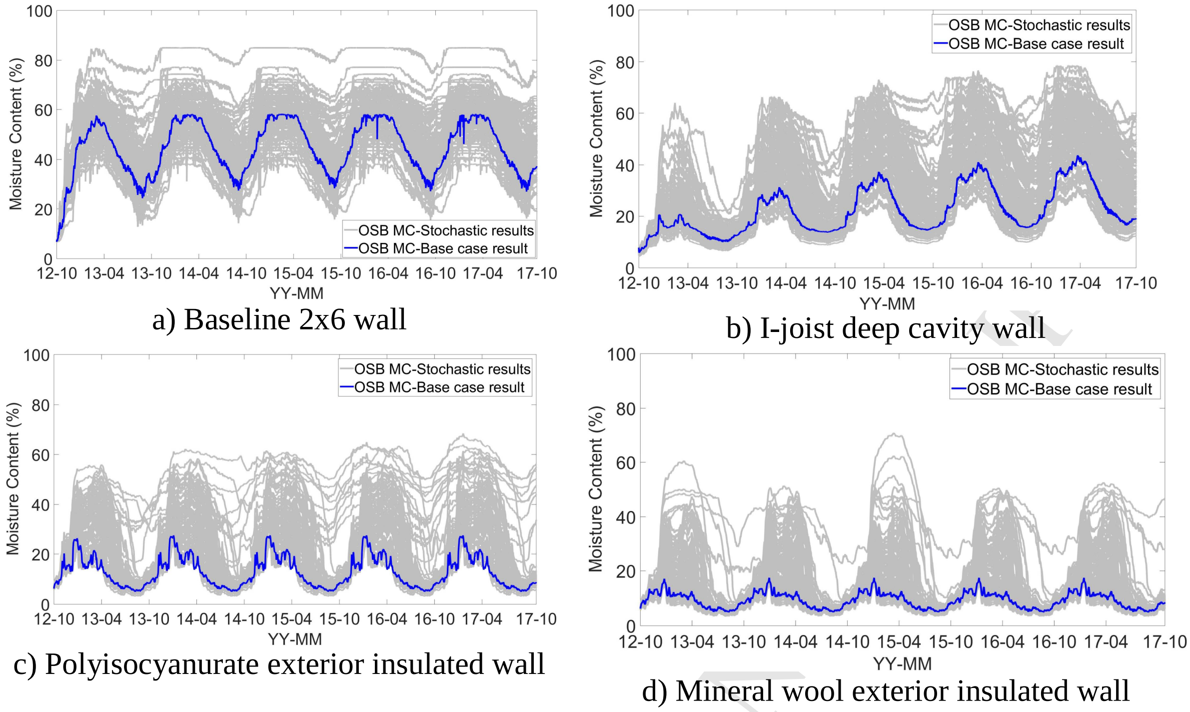
c) Polyisocyanurate exterior insulated wall

d) Mineral wool exterior insulated wall

Fig. 12. Stochastic results of OSB MC with variation of material properties and rain leakage for east-oriented walls in Vancouver

Scenario group 4: Stochastic material properties, air leakage rates and rain deposition factors

Fig. 13 shows the stochastic results of MC of OSB with both rain leakage and air leakage at high internal moisture load. Only simulations results for the east orientation are presented given that the east orientation receives the highest amount of wind-driven rain. It can be seen that the moisture content level and uncertainties of OSB in the walls are higher than those with rain leakage only except for the mineral wool wall. In scenario 4 (the rain leakage and air leakage scenario), the east facing mineral wool wall has a lower MC level than polyisocyanurate wall because the higher vapour permeability of mineral wool wall allows the moisture drying outward. As air convection method is used to simulate the impact of air leakage for mineral wool wall, a 1 mm air layer with indoor temperature and RH is placed outside of vapour barrier (75% Lcd, the depth from interior of OSB to exterior of vapour barrier), which allows the wetted OSB sheathing to be dried by the indoor air, therefore, the moisture content level is lower than scenario 3, in which only rain leakage is introduced.



a) Baseline 2x6 wall

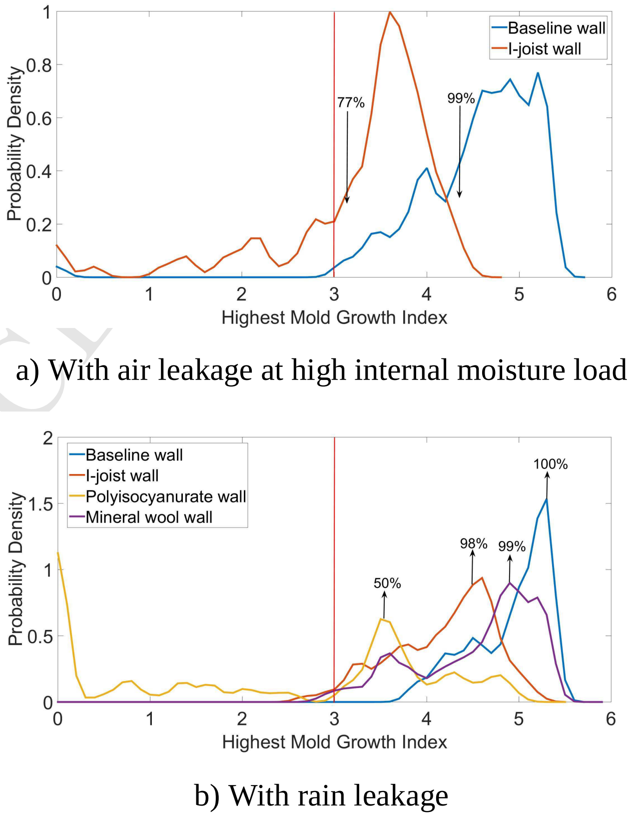
b) I-joist deep cavity wall

c) Polyisocyanurate exterior insulated wall

d) Mineral wool exterior insulated wall

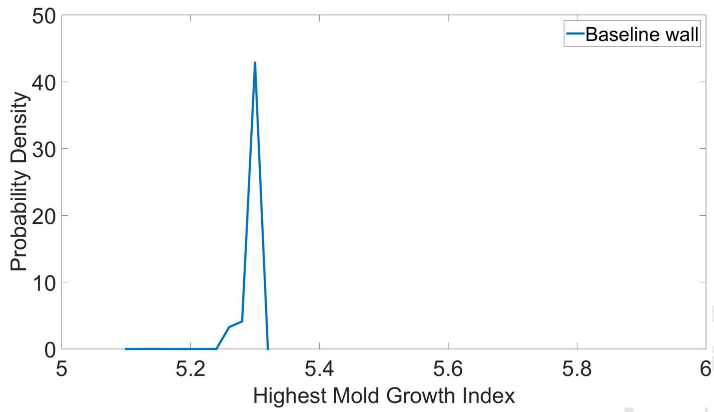
Fig. 13. Stochastic results of OSB MC with variation of material properties, air leakage rates at high internal moisture load and rain leakage for east-oriented walls in Vancouver

3.2.2 Mold growth risk analysis

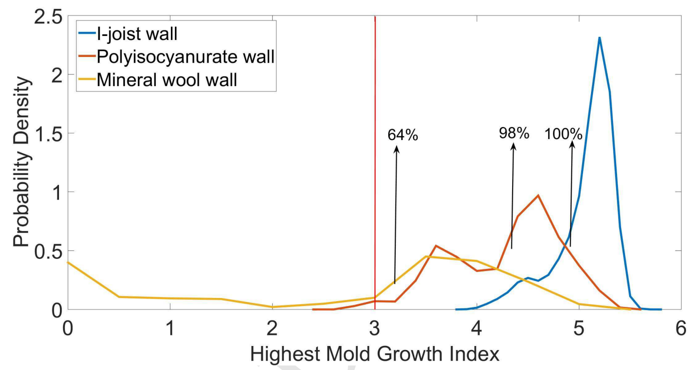


a) With air leakage at high internal moisture load

b) With rain leakage



c) With both air leakage at high internal moisture load and rain leakage (east): baseline wall



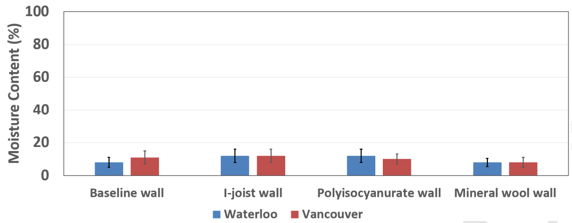
d) With both air leakage at high internal moisture load and rain leakage: highly insulated walls

Fig. 14. Probability density functions of the highest mold growth index for east-oriented walls in Vancouver

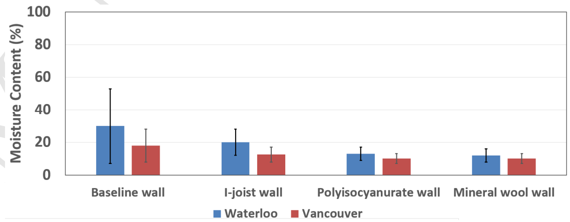
Fig. 14 shows the probability density function of the highest mold growth index for the walls under different scenarios. For air leakage at high internal moisture load scenario, only the baseline wall and I-joist wall have mold growth risks, which are comparable to those in Waterloo (Fig. 8 b). The mold growth risk under rain leakage is much higher than those under air leakage. There is 100% probability of mold growth for baseline wall with 1% rain leakage. For the I-joist wall and mineral wool wall with vapour barrier, the majority of the stochastic cases has mold growth risk. For the polyisocyanurate wall, there is 50% probability of mold growth risk. For the worst scenario, under which the walls are exposed to both air leakage with high moisture load and rain leakage of east orientation, the baseline wall has the most serious mold growth problem, which most of the stochastic cases have the highest mold growth index between 5.2 and 5.3. The I-joist wall and polyisocyanurate wall have higher mold growth risk than the scenarios with air leakage or rain leakage only, while the mineral wool wall has lower mold growth risk than the scenario with only rain leakage. Since the indoor air has a drying effect on the wetted OSB sheathing, the removal of vapour barrier will help reducing the mold growth risk of the mineral wool wall.

3.2 Comparison between Waterloo and Vancouver

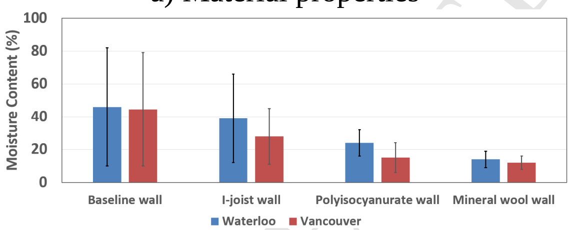
Fig. 15 shows the highest MCs and their uncertainties of OSB in the investigated walls under different moisture loads for two climatic conditions- Waterloo and Vancouver. It can be observed from Fig. 15a that the variation of material properties does not result in significant MC uncertainties for all the walls in both Waterloo and Vancouver. As shown in Fig. 15b, the air leakage leads to a significant MC level and uncertainty for the baseline wall in Waterloo, while the MC level and uncertainty are less significant for Vancouver. The I-joist wall has lower MC level and uncertainty than the baseline wall for both Waterloo and Vancouver. The influence of air leakage on the exterior insulated walls is insignificant at low internal moisture load condition, while under high internal moisture load condition, the MC levels and uncertainties are much more significant for all the walls. The influence of rain leakage is more significant in Vancouver than in Waterloo (Fig. 15d), particularly for the baseline wall and mineral wool wall, which have the higher uncertainty of moisture content than I-joist wall and polyisocyanurate wall.



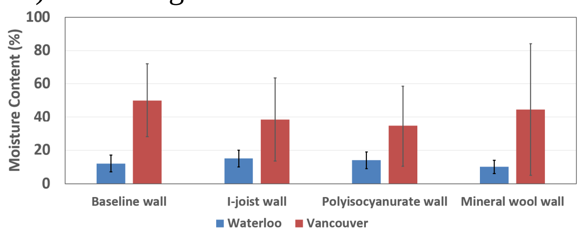
a) Material properties



b) Air leakage at low internal moisture load



c) Air leakage at high internal moisture load



d) Rain Leakage: South (Waterloo) or East (Vancouver)

Fig. 15. Highest MCs and their uncertainties under different scenarios

Table 6 shows the mold growth risks for all the walls under different moisture loads and climatic conditions. In Waterloo, the air leakage with low internal moisture load only results in a low mold growth risk for the baseline wall, while under high internal moisture load, the air leakage leads to a high mold growth risk for the baseline wall and I-joist wall and low risk for the polyisocyanurate wall. The rain leakage does not result in any mold growth risks for all the walls. For the scenario with both air leakage and rain leakage, the risk of mold growth in polyisocyanurate becomes higher than that exposed to air leakage only.

In Vancouver, the air leakage at low internal moisture load does not result in any mold growth risk for all the walls. Air leakage at high internal moisture load condition, the baseline wall and I-joist wall have high mold growth risks, which are similar to those in Waterloo, while the exterior insulated walls have no mold growth risk. The risks caused by rain leakage is much higher than those caused by air leakage, especially for the mineral wool wall, which has vapour barrier and reduces the chance that the penetrated rain water to be dried toward inside. When both air leakage and rain leakage are introduced, the mold growth risk in polyisocyanurate wall is increased because of the condensation caused by air leakage and the low permeance of the exterior insulation. For the mineral wool exterior insulated wall, the mold growth risk is decreased, because air convection method is used to simulate the effect of air leakage, and the dryer indoor air has a drying effect on the OSB sheathing wetted by the rainwater.

Table 7 shows the threshold of the air leakage rate and rain deposition factor for the walls under different moisture load in Waterloo and Vancouver. The threshold is defined as the values of air leakage rate or rain deposition factor that are corresponding to mold growth index of 3. The air leakage rate and rain deposition factor should not exceed these thresholds to avoid mold growth risk.

Table 6 Mold growth risks of the walls under different moisture loads and climatic conditions

Climatic condition	**Scenarios**	**Orientation**	**Baseline wall**	**I-joist wall**	**Polyisocyanurate wall**	**Mineral wool wall**
Waterloo	Air leakage _ low load	North	22%	0%	0%	0%
	Air leakage _ high load	North	97%	79%	28%	0%
	Rain leakage	South	0%	0%	0%	0%
	Air leakage _ high load and rain leakage	South	95%	90%	46%	0%
Vancouver	Air leakage _ low load	North	0%	0%	0%	0%
	Air leakage _ high load	North	99%	77%	0%	0%
	Rain leakage	East	100%	98%	50%	99%
	Air leakage _ high load and rain leakage	East	100%	100%	98%	64%

Table 7 Threshold of air leakage rates and rain deposition factors under different moisture loads and climatic conditions

Climatic condition	**Parameters**	**Orientation**	**Baseline wall**	**I-joist wall**	**Polyisocyanurate wall**	**Mineral wool wall**
Waterloo	Air leakage rate _ low load ($l/m^2 \cdot s$)	North	1.7	NR	NR	NR
	Air leakage rate _ high load ($l/m^2 \cdot s$)	North	0.45	0.95	1.1	NR
	Rain deposition factor	South	NR	NR	NR	NR

Vancouver	Air leakage rate _ low load (l/m^2·s)	North	NR	NR	NR	NR
	Air leakage rate _ high load (l/m^2·s)	North	0.3	1	NR	NR
	Rain deposition factor	East	0.35	0.35	0.65	0.35

4 Conclusions

This paper investigated the hygrothermal performance of highly insulated wood framed walls using a stochastic modelling approach, which considers the uncertainties of material properties, boundary conditions and moisture loads, (i.e. air leakage and rain leakage) under two climatic conditions (cold climate and mild/humid climate). The main findings of this paper are:

- The uncertainties of material properties do not result in significant uncertainties in MC of OSB sheathing for all the walls when there are no air leakage and rain leakage considered for both Waterloo and Vancouver. The moisture content of OSB in the I-joist wall and the polyisocyanurate exterior insulated wall (low exterior vapour permeance) have higher uncertainties than the baseline wall and mineral wool exterior insulated wall (high exterior vapour permeance) when only the uncertainties of material properties are taken into account.

Under climatic condition of Waterloo:

- The moisture content of OSB in the baseline wall with fiberglass insulation is more sensitive to air leakage than the I-joist wall with cellulose fiber. The mold growth risk of the baseline wall is higher than the I-joist wall with air leakage. The air leakage does not result in mold growth risk under low internal moisture load condition for the exterior insulated walls since there is no condensation caused by air leakage. Under high internal moisture load condition, the air leakage will result in mold growth risk for the polyisocyanurate wall with lower risk than the baseline wall and I-joist wall, but the mineral wool wall has no mold growth risk. The rain leakage does not result in mold growth risks for all the walls.
- For the baseline wall and I-joist wall, the increments of MC's uncertainties under air leakage are higher than those under rain leakage. For the exterior insulated walls, the increments of MC's uncertainties under air leakage with low internal moisture load are not significant but slightly higher under high internal moisture load, the increments caused by rain leakage are similar with those under air leakage with low internal moisture load.

Under climatic condition of Vancouver

- The air leakage will not result in mold growth risk for the exterior insulated walls (polyisocyanrate wall and mineral wool wall), but will lead to mold growth risks for the baseline wall and I-joist wall under high internal moisture load condition, and the mold growth risks are similar to those in Waterloo.
- The rain leakage has more significant influence than air leakage. For east orientation, which receives the highest amount of wind-driven rain, the baseline wall, I-joist wall and mineral wool wall have almost 100% probability for mold growth. The polyisocyanurate

wall have lower mold growth risk (50% probability for mold growth) than baseline wall, I-joist wall and mineral wool wall.

- In the scenario with both air leakage at high internal moisture load and rain leakage (east), the baseline wall and I-joist wall have 100% probability of mold growth risk, polyisocyanurate wall has a much higher mold growth risk (98%) than the scenario with rain leakage only (50%). For the mineral wool wall， the mold growth risk is lower than that with rain leakage only (64% compare to 99%).
- The increments of MC's uncertainties under air leakage with low internal moisture load are not significant for all the walls, while under high internal moisture load the increments of MC's uncertainties become significant for the baseline and I-joist wall but still insignificant for exterior insulated walls. The increments of MC's uncertainties are more significant under rain leakage than those under air leakage, especially for mineral wool exterior insulated wall with interior vapour barrier.

Acknowledgement

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- Hygorthermal performance of highly insulated wood framed walls is investigated using a stochastic modelling approach.
- The uncertainties of material properties do not result in significant uncertainties of moisture content and mold growth risks.
- The significance of moisture loads (air leakage or rain leakage) depends on climatic conditions.
- For deep cavity wall, cellulose fiber insulation reduces mold growth risk due to its storage capacity.
- For exterior insulated wall, higher exterior permeance reduces mold growth risks.