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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 2 × 6 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 2 × 6 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.

Nomenclature

Symbol	Parameter	Unit
A	Water absorption coefficient	$kg/m^2 \cdot s^{0.5}$
c	Specific heat capacity of dry material	J/kg 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

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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 [4–12]. 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 2 × 6 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 2 × 6 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 [13–16]. 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 [21–27]. 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 modelling 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 2 × 6 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 modelling approach developed by Wang and Ge is applied to highly insulated wood framed walls [28]. The stochastic modelling 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