Building and Environment 97 (2016) 11–25

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Hygrothermal performance of cross-laminated timber wall assemblies: A stochastic approach

Lin Wang, Hua Ge*

Department of Building, Civil and Environmental Engineering, Concordia University, 1455 de Maisonneuve, Montreal, QC, H3G 1M8, Canada

ARTICLE INFO

Article history:
Received 16 September 2015
Received in revised form
12 November 2015
Accepted 26 November 2015
Available online 2 December 2015

Keywords:
Cross-laminated timber (CLT) wall assemblies
Hygrothermal performance
Stochastic approach
Sensitivity and uncertainty analysis
Moisture content

ABSTRACT

Cross-laminated timber (CLT) panels have the potential market in North America for building mid-rise or even taller structures due to their good structural and fire safety performance, carbon storage capacity, light weight, and prefabricated nature. However, prolonged exposure to moisture during construction and in service is a durability concern for most wood products including CLT. This paper presents the evaluation of the hygrothermal performance of CLT wall assemblies through simulations using a stochastic approach to account for the uncertainty of material properties, boundary conditions, and environmental loads. The moisture content of the CLT panel is used as the performance indicator. The influential factors are categorized into continuous and discrete random variables. The influence of the continuous random variables including material properties, boundary conditions and cladding ventilation rate is investigated under conditions represented by different combinations of the discrete random variables including wall configurations, orientation and rain leakage rate. The critical factors that lead to high moisture content are identified under each condition and the interaction between the discrete and continuous random variables is analyzed. The stochastic results show that the CLT wall assembly with low vapor permeance material placed outboard the CLT panel has a higher risk of moisture problem than CLT wall assembly with high vapor permeance material placed outboard the CLT panel. The sensitivity analysis indicates that the significance of the stochastic parameters on the hygrothermal performance of CLT panel depends on environmental loads, especially the rain load, and wall configurations.

1. Introduction

Cross-laminated timber (CLT) panels have the potential market in North America for building mid-rise or even taller structures due to their good structural and fire safety performance, carbon storage capacity, light weight, and prefabricated nature [1,2]. However, prolonged exposure to moisture during construction and in service is a durability concern for most wood products including CLT. To ensure its long-term durability, its hygrothermal performance needs to be investigated. A previous study focused on field measurements of the hygrothermal performance of CLT wall assemblies with built-in moisture and the comparison between measurements and simulations using a commercially available program [3]. In the previous study, the hygrothermal simulations were performed using the deterministic approach, which were commonly used in studies on wetting and drying of wood-framed assemblies [4-7]. However, the factors influencing the hygrothermal responses are stochastic in nature such as the variability of material properties, boundary conditions as well as the environmental loads. The uncertainties of the input parameters may lead to a deviation between simulation results and the actual performance of the wall assemblies [8-9], consequently, may lead to faulty designs.

The stochastic approach had been applied in several studies investigating the influence of material properties and boundary conditions through hygrothermal simulations [10-13]. The influence of environmental conditions such as rain loads and internal moisture gains on the hygrothermal performance of wall assemblies was also investigated by parametric study [14] and scenario analysis [15]. However, these studies performed stochastic analyses were limited to fixed wall configurations and orientation without the consideration of hazard factors such as rain leakage.

To further investigate the causes for discrepancies between measurements and simulations identified in the previous study [3], a stochastic approach is employed in this paper to take into account the uncertainties in material properties and boundary conditions

* Corresponding author.
E-mail address: hua.ge@concordia.ca (H. Ge).

http://dx.doi.org/10.1016/j.buildenv.2015.11.034
0360-1323/

under various environmental loads and design configurations. The objective of this study is to investigate the uncertainty of simulation results and the sensitivity of moisture content of CLT panel to individual influential factor included in hygric material properties, boundary conditions, and environmental loads. Delphin, a commercial hygrothermal program that is capable of modeling coupled heat and mass transport in porous materials, is used for evaluating the hygrothermal performance of CLT wall assemblies [16]. Firstly, the hygrothermal model is validated by comparing the simulation results to measurements by McClung et al. [3]. Secondly, the validated model is used to evaluate the hygrothermal performance of two CLT wall assemblies- one with low permeance water resistive barrier, and the other with high permeance water resistive barrier using a stochastic approach. The stochastic approach developed is a combination of Latin Hypercube Sampling (LHS) and Partial Ranked Correlation Coefficient (PRCC) method and factorial design method. The moisture content of CLT panel is used as the performance indicator. The impact of each individual influential factor on the hygrothermal performance of CLT panel is quantified by PRCCs. The following sections present methods, results and conclusions.

2. Methods

2.1. Validation of the hygrothermal model

2.1.1. Experimental setup

To investigate the drying and wetting behavior of CLT wall assemblies, the hygrothermal performance of sixteen 0.6 m by 0.6 m CLT panels made of five different wood species (or species groups) and four different wall configurations was monitored over a two-year period under the climatic conditions of Waterloo, Ontario [3]. The five wood species included four Canadian wood species – Western SPF from British Columbia (predominantly lodgepole pine, *Pinus contorta*), Hem-Fir from British Columbia (predominantly western hemlock, *Tsuga heterophylla*), Eastern black spruce (predominantly black spruce, *Picea mariana*), Black spruce from Quebec, and one European spruce (predominantly Norway spruce, *Picea abies*).

In general, the configuration of each test wall included a structural CLT panel on the interior, followed by a rainwater and air control layer, i.e. the water resistive barrier (WRB), exterior insulation, and rain-screen fiber cement panel with a 19 mm air cavity behind the cladding created by plywood furring spaced at 400 mm. The two types of WRB were a vapor permeable (VP) and a non-vapor permeable (NVP) self-adhesive water resistive membrane. On the interior side of the CLT, each assembly included an interior air space built with light wood frame and gypsum drywall. A typical wall section is shown in Fig. 1.

Four categories of wall assemblies were studied: three having high, medium or low vapor permeance materials outside the CLT panels, respectively, but all having an unobstructed wall cavity on the interior side of the panels, which would allow them to dry to the interior freely. The fourth category had the medium permeance construction on the exterior but with a polyethylene sheet on the interior side of the CLT panels, creating a low interior permeance condition. The vapor permeance variations were created with combinations of materials shown in Table 1, generally providing three orders of magnitude of vapor permeance.

The CLT panels were initially wetted with the moisture content (MC) in the surface layers approaching or exceeding 30%. MC pins made of ceramic coated stainless steel nails, thermistors, and RH sensors were installed across the wall assemblies to monitor the hygrothermal behavior of the CLT panels. Six MC pins were installed in each CLT panel, one in the middle of the panel, one at 19 mm from each face, one at 13 mm from each face, and one at 6 mm from the exterior face except for the low interior permeance panels, where the 6 mm depth moisture content measurement was taken from the interior face. Three thermistors per panel were installed in the middle of each panel and 13 mm from each face. These temperature readings were used for compensating the effect of temperature on MC readings. MC readings were also corrected for species. The typical sensor layout and notation for the test assemblies is shown in Fig. 2.

The test wall was located on the east side of the building envelope test facility. The interior of the facility was maintained at 21 °C ± 1 °C and 50% ±3% RH using customized, highly controlled heating, cooling, and humidification systems, with adequate fans and ceiling diffusers to evenly distribute the conditioned air. The choice of 21 °C ± 1 °C and 50% ±3% RH was to represent a typical indoor moisture load for the summer, but a high interior moisture load scenario in the winter. The exterior weather conditions were monitored on the roof of this field test facility. Measurements were taken every hour including temperature, RH, global solar radiation, rainfall, wind speed, and wind direction. The data was collected from Aug. 2011 to Aug. 2013. More detailed information on the experimental setup can be found in McClung et al. [3].

2.1.2. Setting of the hygrothermal model

Delphin version 5.8.3 (released in January 2015) is used for the hygrothermal simulations. The wall assemblies that used Quebec black spruce with low permeance WRB (B1) and high permeance WRB (B2) are selected for analysis in this paper. A detailed description of the selected wall assemblies is shown in Table 2, and the basic material properties of each component are shown in Table 3.

These basic material properties and the material functions including moisture storage function and vapor resistance factor as a function of relative humidity were determined based on the physical characterization tests conducted by NRC [17]. The moisture diffusivity as a function of moisture content of CLT panel was determined based on the laboratory water uptake tests conducted by Lepage [18], in which moisture diffusivity is determined for both

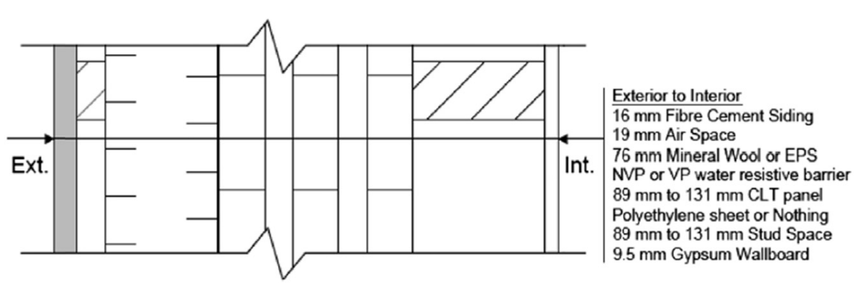

Fig. 1. Cross-section of a typical CLT wall assembly.