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Evaluation of the thermal and structural performance of potential energy efficient wall systems for mid-rise wood-frame buildings

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ABSTRACT

Approximately 30% of energy use in Canada is consumed in buildings, specifically space heating, which can be reduced by constructing thermally-resistant building envelopes. This study evaluates potential innovative energy-efficient wall systems for mid-rise (four to six storeys) wood-frame buildings in terms of thermal and structural performances. Regarding the thermal resistance performance, four wall systems are developed, installed in a full-scale test house, and examined, along with a baseline wall system, using the field data collected. The selection of the wall systems is based on current practice, structural analysis, pre-fabricability, and energy-efficiency. Several sensors are installed on each wall system to measure temperature, heat flow, and relative humidity. In addition, structural tests are conducted to determine the compressive loading capacity of the tested wall systems for both concentric and eccentric loads, where full-scale panels are constructed and tested in laboratory. As a general finding, all the tested wall systems achieved ASHRAE's minimum assembly *R*-value recommendation of RSI 3.45, where the I-joist wall system had the highest *R*-value, while the conventional wall system had the highest load-bearing capacity. This paper recommends I-Joist wall systems for their higher energy efficiency suggesting more future research on efficient end connections to achieve consistent structural performance.

1. Introduction

Buildings account for 30–40% of the total primary energy use and 24% of the generation of greenhouse gases globally [1,2]. If current trends continue, by 2025, buildings worldwide will be the largest consumers of global energy, using as much power as the transportation and industrial sectors combined. Recent studies have found that improving energy-efficiency in buildings is the least costly way to reduce a large quantity of carbon emissions [2]. Meanwhile, the building sector offers significant potential to reduce primary energy use and CO_2 emissions [3] through such measures as reduced heating demand, increased efficiency of the energy supply chain, and greater use of renewable resources for materials and fuels [4]. Reductions in the specific energy demand of buildings and increased use of renewable energy are important measures of climate change mitigation [5]. For this reason, energy-efficiency in buildings is now a primary objective of energy policy at the regional, national, and international levels [6]. Several strategies can be used to realize this potential, including the increased incorporation of energy-efficiency requirements into building standards, such as requirements that specify minimum energy-efficiency for buildings.

Wood-framing is the preferred approach for the building envelopes of low-rise residential facilities and commercial buildings in North America, being that wood-frame building envelopes are lightweight, easily built, durable, renewable, and lower in embodied energy than most alternative building materials [7,8]. The Canadian Wood Council [9] has stated that this is due to the proven performance of properly designed and built wood-frame buildings, which have historically provided strong and lasting housing. Building on the success of low-rise wood-frame buildings, in British Columbia, wood-frame construction solutions for mid-rise buildings have been developed and refined in recent years, leading to more sustainable communities and affordable housing solutions that can positively change the face of North American cities and provide more multi-unit buildings for a fast-growing population. Internationally, the conditions for market growth of multi-storey construction seem to be most favorable in Sweden, the UK, and Germany [10].

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Using light wood-frame structures for constructing mid-rise buildings means that there is higher compressive load bearing on the wall systems. This needs to be addressed by increasing the strength of the walls by reducing stud spacing. The use of more lumber per panel to increase structural performance, however, is accompanied by a significant decrease in thermal resistance performance, since wood has a relatively high thermal conductivity compared to insulation materials, resulting in a thermal bridge between the indoor and outdoor environments. A study by Berggren and Wall [5] has shown the increasingly prominent role of thermal bridges in transmission heat transfer calculations to improve a building's energy performance. However, our research aims to optimize the structural and thermal performance of the selected wall systems taking into account anticipated future building code requirements for both thermal efficiency and structural capacity.

ASHRAE-90.1 [11] has specified energy performance requirements for buildings for different climate zones. Climate zones are determined on the basis of Heating Degree Days (HDD). An HDD is a measure of how cold a location is over a period of time relative to a base temperature of 18 °C [11]. Edmonton, Alberta, where the test house is installed, has a recorded range of 5000 to 6000 HDD. In climate zones of 5000 to 7000 HDD, the range within which Edmonton falls, ASHRAE-90.1 [11] recommends a minimum assembly *R*-value (RSI) for wood-frame buildings of R-19.6 (3.45).

1.1. Research objectives and scope

In the extreme weather conditions of Canada, and North America in general, there is a demand to create thermally-resistant building envelopes. This study aims to develop energy-efficient wall systems for mid-rise construction that can, thermally, mitigate heat loss, and, structurally, increase load-bearing capacity compared to conventional wall systems. Regarding thermal resistance performance, which is quantified in terms of R-value, four different wall systems are developed, manufactured, and installed in a full-scale test house; exposed to the natural exterior climate; and examined for their long-term thermal resistance performance, along with a baseline wall system. The selection of the wall systems is based on specific considerations: current practice; preliminary structural analysis; pre-fabricability; material availability; expected energy efficiency; and population growth, which necessitates more multi-unit buildings.

The general objective of this research project is to identify promising exterior wall systems that can be expected to meet future building code requirements for thermal performance while providing the required structural capability for mid-rise wood-frame construction. The specific goals of the study are as follows:

(a) Evaluate the long-term thermal performance of the selected exterior wall systems exposed to natural outdoor climatic conditions and to controlled indoor conditions;
(b) Evaluate the structural performance of the selected wall systems with laboratory tests; and
(c) Characterize the temperature, air, and moisture (hygrothermal) response of these wall systems in extreme weather conditions and to indoor conditions of humidity and pressure.

1.2. Research methodology

The testing methodology is conducted by installing several sensors on each wall system, including heat flux sensors, thermocouple sensors, and humidity sensors. The extreme weather conditions in Alberta are challenging, even though the indoor environmental quality is maintained by installing aheater, thermistor, and humidifier in order to maintain an average indoor temperature of 22 °C and a relative humidity of 50%. The selected wall systems are: two engineered-wood I-Joist (TJI 230) wall stud systems at spacing of 304.8 mm and 406.4 mm (12 in. and 16 in.), respectively; two 38 mm × 140 mm (2 in. × 6 in.) staggered wall stud systems at spacing of 304.8 mm and 203.2 mm (12 in. and 8 in.), respectively; and a baseline wall system which consists of 38 mm × 184 mm (2 in. × 8 in.) wall studs at a spacing of 304.8 mm (12 in.). The period of data collection is April, 2012 to April, 2014.

The structural performance test focuses on one type of each wall system, (i.e., an I-Joist, a staggered, and a conventional wall system). The objective of the structural performance test is to determine the compressive load capacity of the tested wall systems for both concentric and eccentric types of loads. Full-scale panels with dimensions of 1.2 m × 2.4 m (4 ft × 8 ft) are designed for testing that conform to the specifications of actual wall construction. In order to prevent axial buckling at the wall studs, mid-blocks are fixed between the wall studs, thus increasing the wall panels' loading capacities. As recommended by the American Society for Testing and Materials (ASTM) [12], each type of test is confirmed by testing three like specimens. The primary objective of the study is to select a wall system that strikes an optimal balance between energy-efficiency (high *R*-value) and load-bearing capacity for mid-rise construction.

2. Thermal performance of wall systems

This research is based on field measurements, which, as advanced by Straube et al. [13], are useful primarily because they expose building components to the whole range of conditions experienced by enclosures in service. This means that the boundary conditions are, by definition, realistic in magnitude, rate, sequence, and probability of occurrence. Simulation software is used as a complementary component of this research to estimate the thermal performance of the selected wall systems. Consequently, the results from in-situ data collected are validated by comparing them to simulation results.

2.1. Wall systems selection

The selection of potential wall systems for field and lab testing in this project is based on a number of considerations. Traditional stick-frame construction practice uses 38 mm × 89 mm (2 in. × 4 in.) or 38 mm × 140 mm (2 in. × 6 in.) lumber studs placed at a spacing governed by the type of wall (load-bearing or non-load-bearing) and the amount of load acting upon it [14]. However, load-bearing walls in mid-rise buildings, being subjected to greater vertical and horizontal loading, are likely to have closely spaced studs, ultimately making them less energy-efficient. Our study thus explores the potential of using wall systems comprising engineered-wood I-joists and staggered studs, rather than conventional stud configurations. Engineered-wood I-joists have higher flexural strength and are usually used as horizontal members in floors, thus making them a good candidate to perform well against horizontal loads (such as wind). Moreover, they are expected to have better thermal resistance than traditional lumber studs because of their relatively thinner web. The consideration behind selecting staggered studs is to break the thermal bridging created at the stud locations. It is understood that such configurations may not be suitable for load-bearing walls because the studs that are not connected to sheathing can buckle against their weaker axis. In addition, in order to compare these engineered I-joist and staggered stud options with conventional practice, a 38 mm × 184 mm (2 in. × 8 in.) conventional stud configuration is selected. Use of 38 mm × 184 mm (2 in. × 8 in.) lumber instead of 38 mm × 89 mm