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A review of high *R*-value wood framed and composite wood wall technologies using advanced insulation techniques

Jan Kosny [a,*], Andi Asiz [b], Ian Smith [c], Som Shrestha [d], Ali Fallahi [a]

[a] Fraunhofer CSE, Boston, MA, USA
[b] Prince Mohammad Bin Fahd University, Saudi Arabia
[c] University of New Brunswick, Fredericton, Canada
[d] Oak Ridge National Laboratory, Oak Ridge, TN, USA

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ABSTRACT

The main objective of this study is to indentify advanced wall frame assemblies applicable for residential and small commercial buildings, that have or could reach *R*-values larger than R_{SI} – 3.5 m^2 K/W (*U*-value lower from 0.29). An extensive literature review of existing and past practices is used as the main vehicle to analyze: framing and wall insulation methods, architectural details with focus on minimizing thermal bridges, structural adequacy aspects with respect to gravity and lateral loads, and ability to provide fire and sound breaks. In this paper a wide selection of advance framing wall assemblies is discussed in details with main focus on construction methods, architectural details with minimized thermal bridges, and structural (strength) concerns. High performance wall technologies of consideration include: double walls, Larsen truss walls, optimum or advanced framing walls, walls using distance spacers (furring) and walls made of wood-based composites. Since wood framing for wall applications is mostly used in North America, Scandinavia, and Central Europe, this study is focused on research studies from these regions. In addition, field test studies are presented discussing an application of high *R*-value of new and retrofitted wall assemblies in actual test houses that have been constructed and being currently monitored.

1. Introduction

Various super insulated homes with high *R*-value wall frame assemblies have been built and investigated in North America and Europe since the energy crisis in the early 1970s. Even until today, a number research projects focused on high thermal performance envelopes has still been high due to increased concerns on issues related to environmental impacts (sustainable or green construction), saving more building energy consumption (zero net energy building), and higher thermal and occupant comfort expectation than those in the past. Wood-based wall technologies are widely considered as primarily building materials for low-environmental-impact buildings [1–4]. For example, current research performed by the Mid Sweden University demonstrated that both the primary energy consumption as well as the CO_2 emission generated during production of materials used in building construction are lower in case of wood-framed constructions than for concrete buildings [5].

In the past Oak Ridge National Laboratory (ORNL) Buildings Technology Center (BTC) conducted in Oak Ridge, TN, U.S.A., a detailed experimental and numerical analysis of over 150 wall technologies including advanced wood-framed walls. For architectural details thermal performance comparisons are available base on results of detailed three-dimensional finite difference modeling. For each considered wall technology clear wall computer model was validated against the hot-box test data. This information is available as the Whole Wall *R*-value Database [6–9]. Downloadable from Internet Whole Wall *R*-value Calculator enables direct performance comparisons of wall technologies and detailed analysis of wall architectural components [10]. In addition, a wide selection of high thermal performance walls constructed in actual homes have been studied and monitored by the ORNL [11]. Some of these walls have effective *R*-values exceeding R_{SI} – 4.4 m^2 K/W. The key wall technologies used in ORNL research houses include structural insulated panel (SIP), optimum value engineering (OVE), double wall with composite framing, and exterior insulation and finish system (EIFS).

In recent study conducted for the U.S. Department of Energy Building America Program by Straube and Smegal [12] summarized high *R*-value of walls that have been tried out in North American residential buildings, ranging from double stud walls to exterior insulation finish wall system. The main analytical method in their study was two-dimensional steady-state heat flow model to quantify thermal performance of wall assemblies with incorporated some effects of integral structural components. Additional

* Corresponding author. Tel.: +1 617 714 6525.
E-mail address: jkosny@fraunhofer.org (J. Kosny).

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quantitative measure related to durability was also imposed using a simplified one-dimensional hygrothermal model to estimate potential risk of condensation of those various walls [13–15]. One of the main conclusions obtained in that study was that adding exterior insulation to most wall assemblies has many advantages in term of thermal performance aspect due to continuous thermal break provided. They also concluded that new wall frame assemblies with high R-value insulation materials could have durability issue due to high condensation risk in outer layers of building envelope (e.g. sheathing), and careful detailing has to be practiced to avoid it.

During last two decades research from Fraunhofer IBP (Institute for Building Physics), Germany has investigated different ways of constructing high energy efficient walls while providing excellent long term durability [14]. It was demonstrated that from long term durability perspective, in heating dominated climates, destructive temperature or humidity conditions caused by poor insulation and inappropriate material selection can be easily avoided. It was also found that for many constructions working well in specific climates, changes in application location or building operation schedules may lead to hygrothermal and energy performance problems within the structure [15].

Several high performance insulation options including vacuum insulations and aerogels have been recently analyzed and tested by Fraunhofer CSE, U.S.A. in wall retrofit applications [16,17]. In 2010 a demonstration project was initiated with one story wood framed building insulated with vacuum insulation. In this case Vacuum Insulation Panels (VIPs) were sandwiched with expanded polystyrene (EPS) foam for mechanical protection and installed on the exterior face of the wall.

In Canada thermal performance of residential and other buildings has become a dominant focus of changes to construction practices with special requirements for prescriptively built housing and small buildings being approved in 2012 (Part 9 of the National Building Code), and a more generalized National Energy Code of Canada for Buildings published in 2011 (http://www.nationalcodes.nrc.gc.ca/eng/necb/index.html).National Research Council of Canada (NRC) has conducted several projects developing high thermal performance wall assemblies that can be applied in extreme northern climates [18]. Several construction criterions applicable in the northern Canada including constructability, cost, durability, sustainability, socio economic have been imposed before selecting suitable building envelope systems. Based on this study, NRC has recommended using double stud wall, standoff truss wall, structural insulated panel, or structural insulated concrete wall system in wall housing assemblies to reach R-value larger than R_{SI} – 5.3 m^2 K/W. Some of these walls have been tested in the NRC laboratory for further verification.

In principle, thermal performance of wall frame assemblies can be increased by either: applying thicker and wider insulation space in wall cavity; installing insulating sheathing; improving thermal resistance of insulation materials; reducing or eliminating thermal bridging; or applying airtight construction. Combination of these methods is normally applied in practice to reach high R-value and sometime to improve other (wall or building) performance aspects such as durability, constructability, and costs. The main objective of this study is to indentify wood frame or composite assemblies applicable for residential and small commercial buildings that have or could have R-values larger than R_{SI} – 3.5. In this paper, double wall, Larsen truss wall, optimum or advanced framing wall, European walls, and walls with furring and composites are considered. Advance framing assemblies amongst other walls will be discussed in details with main focus on construction methods, architectural details with minimized thermal bridges, structural (strength) concerns, and capability of providing fire and sound break. Since the scope of this work is mostly on wood-frame or wood-based composite assemblies, other types of high R-value walls such as for example Structural Insulated Panels (SIP) are not covered. Advantages of using balloon framing construction in minimizing thermal bridges between floors are discussed in certain applications. Utilization of engineered wood composites to deal with strength requirement and reduced material sizing to accommodate insulation placement is also presented. Case studies are discussed using actual test houses constructed using selected high thermal walls performance to demonstrate their effectiveness in reducing building energy consumption.

2. Prospect reductions of whole building energy consumption as a function of improvements in R-value

Building envelopes play an important role in the heat transfer between the exterior and the interior spaces of the building. From a thermal perspective, a well-performing wall is one that contributes to thermal comfort inside the building with minimum consumption of space conditioning energy [1,19]. During the last two decades, in the U.S. hundreds of building envelope technologies have been evaluated using a hot-box testing and advanced numerical thermal analysis. This collection of technical information, field and lab test thermal performance data, and three-dimensional thermal analysis, enables an objective evaluation of the existing building envelope technologies. R-values or U-values have been used for decades as measures of thermal performance of building envelope components. For most wall systems, the part of the wall that is traditionally analyzed, that is, the flat part of the wall that is uninterrupted by details (clear wall), comprises only 50–80% of the total area of the opaque wall. The remaining 20–50% of the wall area is not analyzed nor are its effects incorporated in the thermal performance calculations. For most of the wall technologies, traditionally estimated R-values are 20–30% higher than overall wall R-values [6,10]. Such considerable overestimation of wall thermal resistance leads to significant errors in building heating and cooling load estimations.

The DOE-2.1E and Energy Plus computer codes were utilized to simulate a single-family residence in representative U.S. climates. A reason for selection of this computer tool is coming from the fact that this building model had been extensively validated in the past over the field experimental data [20,21]. The standard building selected for this purpose is similar to a single-story ranch style house that has been the subject of previous energy efficiency modeling studies [22]. U.S. residential buildings' standards, including ASHRAE 90.2 [19], are based on the whole building energy analysis performed with the use of the same house. In this study ten lightweight wood-frame walls of R-values from 0.4 to 6.9 m^2 K/W were simulated in ten U.S. climates. The heating and cooling loads generated from these building simulations are used to estimate the relation between wall R-value and whole building energy consumption in conventional wood-framed house.

Numerical results demonstrated that wall R-value change between most-commonly used today in North American residential buildings R_{SI} – 2.2 m^2 K/W and expected in the close future R_{SI} – 3.6 may generate between 5% and 8% changes in the building-envelope-generated whole building energy consumption (Fig. 1). Considering that in most of North American residential buildings, walls may generate in average up to 25% of total loads associated to building envelopes (U.S. DOE Building Energy Data Book – http://buildingsdatabook.eren.doe.gov/), it is a substantial improvement of the whole building performance generated by only a single building enclosure component (like wall). In that light, wall framing improvements can be considered as an important source of future energy savings in residential buildings.