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Performance of 8 Cold-Climate Envelopes for Passive Houses

Master's Thesis

Bibliographic information published by the German National Library:

The German National Library lists this publication in the National Bibliography; detailed bibliographic data are available on the Internet at http://dnb.dnb.de .

Imprint:

ISBN: 9783656269960

This book at GRIN:

https://www.grin.com/document/200508

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GRIN Verlag

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A Thesis Submitted to the Faculty of the Graduate School of the University of Minnesota

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8/30/2011

Submitted in Fulfillment of the Requirements for the Degree of Master of Science in Architecture, Sustainable Design Track

Acknowledgements

The author wishes to express sincere appreciation to the Center for Sustainable Building Research (CSBR) for their extended long-term support, and especially to William Weber, Senior Research Fellow at the CSBR, for all his work as advisor, thesis committee chair, and friend. A great deal of additional guidance, knowledge, and time was offered by Pat Huelman, Associate Extension Professor in the Department of Bioproducts and Biosystems Engineering, who first introduced the author to the wonderful world of building science. Special thanks are in order to Lucas Alm, Adjunct Assistant Professor, for stepping in as thesis committee member after the retirement of Steve Weeks, former Director of Graduate Studies at the College of Design.

The author also wishes to extend a tremendous thank you to the Research Centre on Zero Emissions Buildings at the Norwegian University of Science and Technology (NTNU), and Anne Grete Hestnes, Director, who graciously extended her assistance and the support of her center and university. Many thanks to the NTNU professors and SINTEF researchers who generously offered their time and support throughout the 2010/2011 academic year: especially Sivert Uvslokk, Arild Gustavsen, Stig Geving, and Berit Time. Tusen takk!

One final thank you to the U.S. Fulbright Program, for providing funding and the opportunity to study abroad at the Research Centre on Zero Emissions Buildings in Norway.

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Abstract – “Performance of 8 Cold-Climate Envelopes for Passive Houses

While the design and construction of envelopes for Passive House certified homes in central European climates is well developed and has achieved widespread acceptance and reliability, the same cannot be said in colder climate regions such as the upper Midwest (DOE climate zones 6 and 7) and Scandinavia. The objective of this research was to study some of the typical building performance issues relating to Passive House envelope construction for single family homes in cold climates by testing and developing a group of 8 envelope options. Typical issues include unfamiliarity with performance of thermal bridge details, added embodied energy and carbon due to increased insulation and structure, and increased risk of moisture damage due to thicker, multi-layered assemblies and smaller drying potentials. The envelopes were tested and developed to meet set levels of moisture safety, life cycle energy and carbon impacts, and Passive House thermal bridging and energy performance requirements. The options chosen for study (listed below) were based on envelopes that have been used for Passive House and low-energy projects in cold climates, including Minnesota, Wisconsin, Maine, Illinois, Norway, and Denmark. A model single family home set in Minneapolis, MN was used as the basis for comparison for a number of software analyses. Athena life cycle analysis software was used to determine embodied energy, carbon, and environmental impacts of the envelope types. WUFI hygrothermal modeling was used to determine moisture performance and risk relating to mold growth. The EN ISO 6946 2-D U-value calculation protocol was used in conjunction with the Passive House Planning Package (PHPP) to ensure that the energy efficiency requirements set by the Passive House Institute were met, while THERM software was used to determine the performance of a selection of thermal bridge details. Although significant variation was found in the performance of these eight types, all envelopes were found capable of meeting the energy efficiency and thermal bridging requirements of the Passive House certification in a cold, Minnesota climate, while maintaining moisture safety, durability, and significant life-cycle energy and carbon savings. These findings demonstrate that even for cold climates, a variety of envelope types can be used for certified Passive Houses.

Envelope options: 1) Advanced 2x6 framing with interior cross strapping and exterior insulation, insulated with mineral wool, 2) Advanced 2x6 framing, insulated with spray polyurethane foam and exterior rigid foam, 3) Double 2x4 stud wall, insulated with blown cellulose, 4) I-joist (TJI) balloon framing, insulated with blown fiberglass, 5) Insulated concrete form wall (ICFs), using EPS insulation, 6) Concrete block wall, insulated with exterior mineral wool, 7) Massivtre/Structural engineered panel (SEP), insulated with exterior rigid foam, and 8) Structural insulated panel (SIP), using EPS insulation. For comparison, a base option was also studied: Standard 2x6 framing (16 inches on center) with fiberglass batt insulation.

Introduction

This research investigates the characteristics of 8 Passive House envelope types in terms of the following topics: 1) insulation value, 2) thermal bridging, 3) overall energy performance, 4) moisture management, and 5) embodied energy and life cycle environmental impacts.

As one of the primary human activities, building has a tremendous impact on the environment. The construction and operation of buildings is estimated to contribute between 30% and 50% of the carbon dioxide and other global warming gases responsible for climate change[1] (U.S. Green Building Council, 2011). Additional environmental impacts from buildings include habitat loss or disruption from mining and forestry activities, air and water pollution from the burning of fossil fuels for electricity and heat, and resource consumption and waste production associated with the fabrication of building materials and building construction, renovation, and demolition. In recognition of the impact buildings have on the environment, governments and organizations worldwide have recently developed a large number of sustainable building rating systems, guidelines, and certifications. The goal of these programs is to reduce the environmental impact of buildings while improving the indoor environmental quality for the occupants. Some of these programs are holistic in nature, such as the U.S. Green Building Council's LEED rating and certification system, which seeks to address many aspects of sustainable building design from indoor environmental quality, through site design and water use, to energy use. Other programs such as Passive House certification are strictly focused on a single environmental issue, most commonly energy use. This research is focused on Passive House certification and its implications for the design, construction, and durability of envelopes in very cold climates including northern North America and Scandinavia.

The Passive House concept grew from early experiments in North America with super-insulated homes. Learning from these early attempts, professors Bo Adamson of Sweden and Wolfgang Feist of Germany developed the first true Passive House in Darmstadt, Germany in 1990. In 1996, Feist decided to expand the concept into a practical approach to meet housing and energy needs[2] (Klingenberg, Kernagis, & James , 2008). He founded the Passive House Insitute and initiated a certification scheme using the new Passive House Planning Package, an Excel-based energy simulation program. Today, Passive House certification has grown into one of the most popular, widely-used energy efficiency standards in Europe, where tens of thousands of homes and other small buildings have been built and certified to date. Enough certified Passive Houses have been built to generate considerable industry interest. Companies have developed a wide range of specialized building products including foundation systems, windows and doors, ventilation ducts, and air source heat pumps to meet the demands of the program. With large numbers of these products available and a construction industry that has achieved a level of familiarity and comfort with the required elements of certification, Passive Houses in central Europe are now beginning to achieve cost parity with standard methods of construction. The adoption of the Passive House certification standard has been slower in colder climates such as Scandinavia and much of North America, but is beginning to grow quickly, with hundreds of homes currently under review for certification in the United States.

Passive House certification is frequently touted as one of the most stringent energy efficiency standards in the world, commonly requiring an energy use reduction of anywhere from 65-85% compared to standard code construction. This level of efficiency is not arbitrary; rather, it was developed based on the notion that a sustainable civilization must exist on available renewable energy resources. After dividing this available pool of energy by the current population of the earth, and further subdividing between basic needs such as transportation, industry, and building/housing requirements, a primary energy budget of 120 kWh/m2/yr (38.1 kBtu/ft2/yr) was calculated for housing. This is based on the assumption of 35m2 (380ft2) of living space per person. For the purpose of the certification standard, the energy budget is applied worldwide irrespective of climate or other conditions. Although the validity of this approach can be debated, it has proven valuable in central European climates for a couple of reasons. First, the strict energy budget requires a steep reduction in energy use compared to standard construction, especially in regards to heating energy for the moderately cold European climate. The reduction in heating energy allows a small amount of heated ventilation air to satisfy the heating load of the building, eliminating the need for large radiators, boilers, or forced-air furnaces. This compensates for the increased cost of high-efficiency windows and doors, and higher levels of insulation. Second, energy use is reduced to the point where it becomes feasible in most situations to meet the remaining energy demand with renewable energy generated on site, typically with solar panels. This allows Passive House certified buildings to achieve net zero energy, while restraining the cost and size of expensive renewable energy systems.

This research was carried out primarily in Minnesota and Norway. In these cold climates, as in much of the Midwest and Scandinavia, the majority of energy use in homes and small buildings is for space heating. To achieve the level of energy efficiency required for Passive House certification, it is absolutely necessary to dramatically reduce space heating energy consumption. High-efficiency heating equipment is a must, but more critically, the heat load, or demand, must be reduced. This is accomplished primarily through improvements in the performance of a building's envelope, or external shell, such as high-performance triple-glazed windows, increased levels of insulation, thermal bridge-free construction, and airtight enclosures. To address these issues, the Passive House Institute has established some recommended guidelines:

"thermal bridge free construction" with Ψ values </= 0.01 W/m/K
whole window U-values </= 0.8 W/m2/K (U-0.14, IP)

While most energy codes don't set performance standards to address heat loss from thermal bridges, window performance is regulated. Passive House windows provide roughly 2.5 times the insulation of standard windows in the United States, and 1.5 times that of standard windows in Norway. The Passive House Institute has also established some performance requirements:

air tightness (infiltration) </= 0.6 air changes per hour (ACH) @50Pa
specific space heat demand </= 15 kWh/m2/yr (4.75kBtu/sf/yr)

The requirement for air infiltration is roughly 4-5 times tighter than the standard level of air tightness achieved in typical residential construction in Minnesota[3] (Sheltersource, 2002) and Norway. The requirement for space heating demand typically results in an 85% reduction in heat load compared to new single-family homes built to current Minnesota energy code. This dramatic reduction is generally achieved by meeting the other requirements and recommendations listed above, in addition to improving the insulation value of the envelope. Although the specific R-values for external walls, roof, and floor can vary according to the climate, achieving the 15 kWh/m2/yr target typically requires R-values 2-4 times higher than those required by energy codes in Norway and Minnesota.

Together, these envelope and space heating recommendations and requirements help a Passive House achieve the final requirement for overall energy use:

specific primary energy demand </= 120 kWh/m2/yr (38.1 kBtu/sf/yr)

This requirement pertains to the building's total energy use including heating, cooling, lighting, appliances, etc, and guarantees that the worldwide energy budget calculated for housing is met by every certified Passive House.

As the need for dramatic reductions in the carbon intensity and energy use of buildings becomes clear, Passive House certification continues to grow and expand into colder climates. However, in very cold climates such as those found in Scandinavia and the northern parts of North America, high levels of insulation and airtight enclosures can pose difficulties in envelope design, assembly, and durability. For example, reducing heat flow through walls with increased insulation can reduce the energy available to dry out moisture within them. In addition, tighter envelopes can increase the potential for trapping moisture. A higher level of moisture fosters mold growth, decreasing indoor air quality (IAQ) and eventually leading to decay of the structure. Moreover, as the level of insulation is increased, the energy expended in manufacturing and construction grows. This extra "embodied energy" cuts into the energy savings the envelope is meant to provide. Finally, as insulation is increased, a greater proportion of heat is lost through thermal bridges[4] (Christian & Kosny, 1996) – intersections or penetrations in the envelope where the insulation is not continuous. Without greater attention to insulating or minimizing these thermal penetrations, the effectiveness of the added insulation is reduced and Passive House certification could be jeopardized. Therefore, the performance of Passive House envelopes needs to be considered in light of the following topics: 1) insulation value, 2) thermal bridging, 3) overall energy performance, 4) moisture management, and 5) embodied energy and life cycle environmental impacts.

The purpose of this research was to evaluate a group of eight envelope types which have been used for Passive House and low energy projects in very cold climates, equivalent to DOE climate zones 6-7. The envelopes were selected, developed, and tested for performance in each of the topic areas mentioned above. The key objective was to determine which envelope types could be designed for moisture safety in these climate conditions while simultaneously meeting the demands of Passive House certification and providing life cycle savings in energy and carbon emissions. This research extends similar work that has been done for Passive House envelopes in central European climates (contained in resources such as the *Passive House Bauteilkatalog*) to envelope types in more common use throughout North America and Scandinavia.

Each of the 5 topics forms a section in this research paper. Within each topic, the performance of all eight envelope types was analyzed using an appropriate software program and/or standardized techniques. Each topic generally begins with a discussion of relevant terms and concepts. This is followed by a brief description of methodology. (A more detailed discussion on methodology can be found in Appendix A.) Performance results, analysis, and comparison with the base case envelope generally conclude each section. The topics are arranged as follows:

1) Selection of envelope types from case studies and calculation of thermal resistance using EN ISO 6946:2007, a standardized 2-dimensional U-value calculation technique.

2) Thermal bridge analysis for a selection of thermal bridge details, with heat loss values calculated using Therm software, version 6.3.

3) Verification of Passive House-level energy performance, using a basic model home in Minneapolis, MN as input for the Passive House Planning Package (PHPP) version 2007, the energy modeling software used for official Passive House certification.

4) Modeling of hygrothermal (moisture) performance and assessment of mold growth risk, using Wärme Und Feuchte Instationär (WUFI) Pro software, version 5.1.

5) Life-cycle performance in terms of energy and carbon emissions, and modeling of additional environmental impacts, using Athena Environmental Impact Estimator, version 4.1.

As previously mentioned, the particular envelopes chosen for this research were selected and developed from cold-climate Passive House and low energy case studies. These envelope types generally work as a system, meaning that above grade walls and roof function together to create a continuous layer of insulation and an air tight boundary. Thus, above grade walls are paired with a matching roof construction to complete the above grade envelope. For example, SIP panel walls are paired with a SIP panel roof, I-joist-framed walls are paired with an I-joist roof, and concrete ICF walls are paired with a concrete roof. In terms of analyzing the research results, the intention of this pairing was to understand the full implications of each particular construction type.

In the case of the ICF envelope, the above grade walls could be extended below grade with very little change. In most cases, however, the above grade envelope was not suitable for below grade use and was paired with a different assembly. The below grade walls for most envelope types consisted of a poured concrete wall 8 inches thick (203mm), insulated with 12 inches (305mm) of rigid type II EPS and finished with an interior layer of gypsum board. In all cases, the bottom of the external envelope was a 4 inch (102mm) thick concrete floor slab, insulated with 14 inches (356mm) of high density type IX EPS foam. The envelope types selected for analysis were as follows:

1) **Advanced Frame with Cross Strap**

"Advanced" 2x6 stud wall with interior cross strapping and exterior insulation, insulated with mineral wool. Roof – "Cold attic" light frame wood truss construction, with interior cross strapping, insulated with blown cellulose and a layer of mineral wool batt insulation between the strapping.

Note - "Advanced framing" refers to framing with studs 24 inches on center (601mm) in line with roof trusses, single top and bottom plates, 2-stud corners with clips for drywall attachment, and insulated headers using metal brackets for support rather than additional "jack" studs.

2) **Advanced Frame with SPF**

"Advanced" 2x6 stud wall, insulated with spray polyurethane foam (SPF) and unfaced exterior rigid polyisocyanurate foam. Roof – "Cold attic" light frame wood truss construction, insulated with a 1 inch layer of SPF and blown cellulose on top.

3) **Double Stud**

Double 2x4 stud wall, insulated with blown cellulose. Roof – "Cold attic" light frame wood truss construction, insulated with blown cellulose.

4) **TJI Frame**

I-joist (TJI) balloon frame wall, insulated with high-density blown fiberglass. Roof – TJI roof construction, insulated with high density blown fiberglass (contains loft space).

5) **ICF**

Insulated concrete form (ICF) wall with additional exterior EPS insulation. Roof – Flat pre-cast hollow-core concrete plank construction, insulated with exterior polyisocyanurate foam.

6) **Mass wall**

6 inch concrete block wall, insulated with exterior mineral wool. Roof – "Cold attic" light frame wood truss construction, insulated with blown cellulose.

7) **SEP panel**

Massivtre/Structural engineered panel (SEP) wall, insulated with exterior foil-faced polyisocyanurate foam. Roof – Wood truss construction, insulated with exterior foil-faced polyisocyanurate foam (contains loft space).

8) **SIP panel**

Structural insulated panel (SIP) wall, using integral EPS insulation, with additional unfaced exterior polyisocyanurate foam. Roof – SIP panel roof, with additional unfaced exterior polyisocyanurate foam (contains loft space).

In addition, a non-Passive House base option for comparison, based on current MN energy code:

9) **Base case (standard frame)**

Standard 2x6 framing 16 inches (400mm) on center with fiberglass batt insulation between the studs. Roof – "cold attic" light frame wood truss construction, insulated with blown cellulose.

A more detailed, pictorial description of the envelope types developed and analyzed for this research is shown on the following pages. As much as possible, the envelopes use real building products and material dimensions.

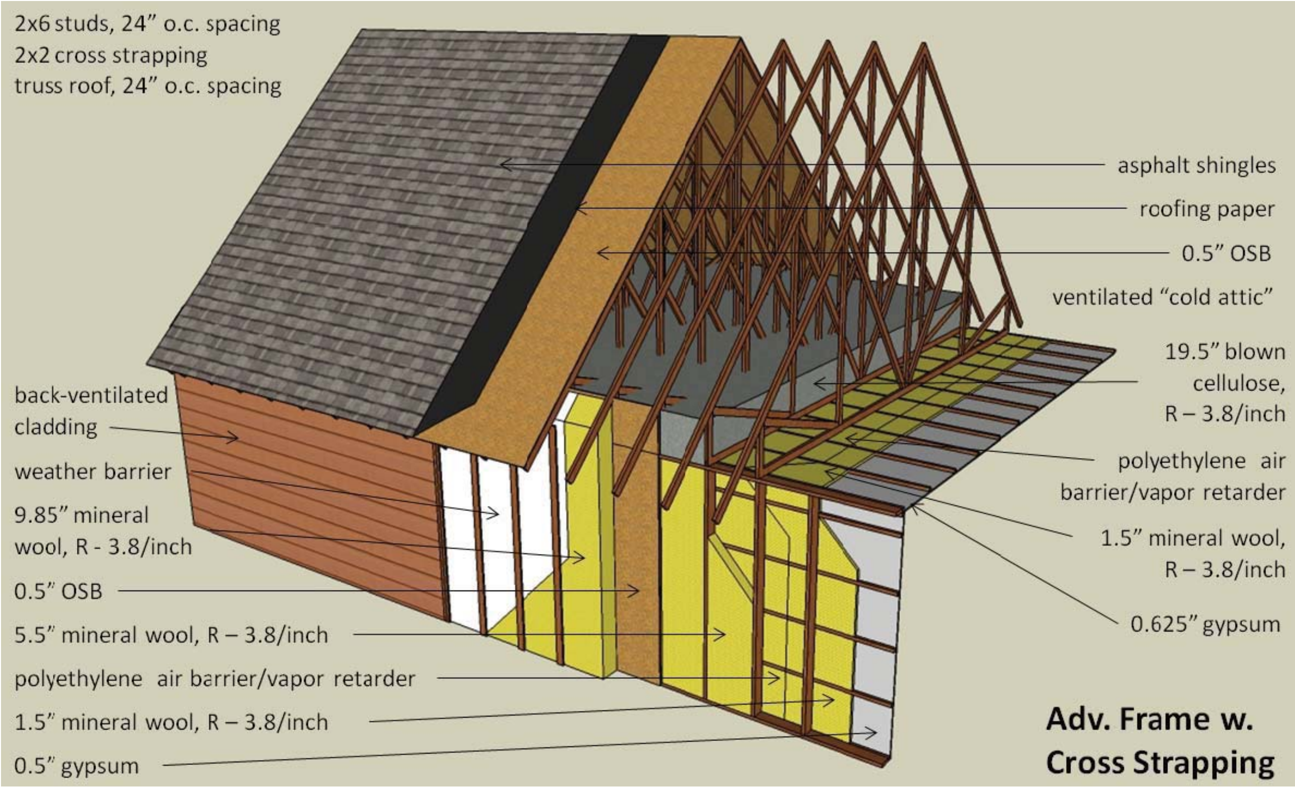

Figure 1) Advanced Frame with interior cross strapping and mineral wool.

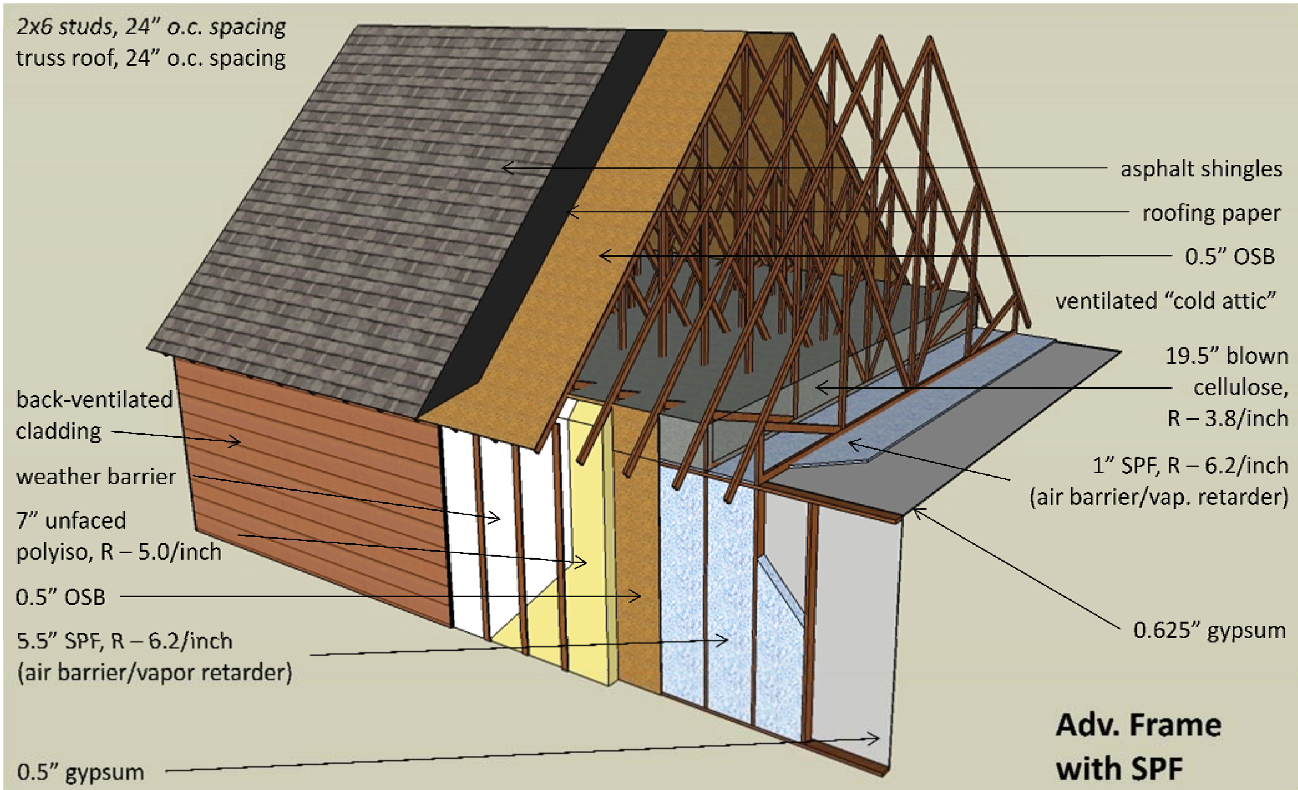

Figure 2) Advanced Frame with spray polyurethane foam (SPF).