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Editorial
Performance-Based Seismic Retrofit of Soft-

Wood Design FOCUS

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In This Issue:

Building Envelope Design for Energy Efficiency and Durability

In The Next Issue:

Full Scale Testing of Wood Buildings

Editorial

The recent trend toward improving building energy performance, as reflected for example by energy code requirements and green building certifications, provides design and construction professionals with both challenges and opportunities for innovation. Building envelope (or enclosure) design plays a critical role in building energy consumption. Envelope design also has extremely important implications for durability, health, and comfort.

The first article in this issue of *Wood Design Focus* highlights a new design guide for energy-efficient building enclosures. This guide was developed by FPInnovations and several partners in response to the rapidly changing energy code requirements across Canada and the United States. Several types of wood building systems are addressed, with a focus on multi-unit residential buildings, including platform wood-frame construction, cross-laminated timber construction, and the use of non-bearing wood-frame infill walls in both post and beam structures and concrete structures. In addition to numerous high-quality illustrations, this guide includes a wealth of information on building science, thermal performance, moisture control, and detailing of key interfaces.

Crawl spaces are often historically and anecdotally associated with dampness more so than other foundation types. The second article provides an overview of design factors that are critical for avoiding moisture problems in crawl spaces. The article summarizes a number of research findings and current recommendations.

Design professionals use a variety to software tools for structural analysis, building energy analysis, etc. One type of analysis that is not yet main-stream but is being used more widely is hygrothermal (heat and moisture) analysis. As building assemblies change in response to energy code requirements, green building standards, new building materials and systems, and new methods of construction, the need to assess moisture performance risks increases. The third article provides a brief introduction to hygrothermal simulation and gives a sense of the usefulness and limitations of this design tool for identifying potential moisture performance problems.

The fourth article addresses corrosion of metal fasteners embedded in wood. Corrosion may be a concern with certain preservative treatments when the wood remains wet for long periods of time. The article illustrates how hygrothermal simulation can be used to predict fastener corrosion in wood and how corrosion affects the strength of wood-metal connections. Research of this nature may prove useful for determining service conditions that warrant use of corrosion resistant fasteners.

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Dedication

In Memory of Charlie Carll, 1954 – 2013

Born July 2, 1954, Charles George Carll was the son of Sherman B. and Patricia G. Carll of Commack, New York. Charlie died at his home in Madison, Wisconsin, on August 17, 2013.

Charlie received a Bachelor of Science in Wood Industries from West Virginia University in 1976 and a Master of Science in Wood Technology from the University of Idaho in 1979.

In September 1979 Charlie began a nearly 32-year career at the U.S. Forest Products Laboratory (FPL) in Madison, Wisconsin. He started as a Forest Products Technologist in Structural Composites Research. In May 1989 he transferred to Wood Drying and Moisture Management, where he began work in the field of moisture management in buildings with Anton TenWolde.

In 1993 Charlie began what would become extensive involvement in American Society for Testing and Materials (ASTM) Committee E-6 on the performance of buildings. He made significant contributions to the development of three new ASTM standards, each dealing primarily with issues of water intrusion into building walls. As a task group chair, he was responsible for the extensive revision, in 2000, of a wide-ranging standard concerning moisture damage to buildings. He also served as a technical editor to the Journal of ASTM International.

Charlie retired from FPL on July 30, 2011. Over his career, Charlie co-authored numerous publications on a range of topics: mechanical properties and durability of wood structural composites; durability and performance of hardboard siding; moisture-related properties of wood; measurement of humidity and wood moisture content; decay of wood and wood products in buildings; air pressures and air flows in walls; moisture performance of wood-frame walls; moisture control in crawl spaces; and performance of permanent wood foundations.

Charlie Carll will be remembered fondly for his love of wood, personal and professional integrity, dedication, thoughtfulness, and generosity.

A New Design Guide for Energy Efficient Wood-Frame Building Enclosures

Jeiying Wang, Ph.D., and Graham Finch, P.Eng.

Abstract

FPInnovations recently published an energy efficient wood-frame building enclosure design guide in collaboration with RDH Building Engineering Ltd., the Homeowner Protection Office, Branch of BC Housing (HPO), and the Canadian Wood Council (CWC). The guide was developed in response to the rapidly changing energy efficiency requirements for buildings across Canada and the United States. It was designed to assist architects, engineers, designers, and builders in meeting the increasingly stringent energy efficiency requirements, to improve the thermal performance of wood-based building enclosures, and to advance good design and construction practices, with a focus on the marine to cold climate zones. It covers the major requirements for good thermal performance of wall and roof assemblies for buildings built under the North American codes and standards. The guide applies building science fundamentals, existing best practices, and relevant research to the design of energy-efficient and durable wall and roof assemblies and building enclosure detailing for key interfaces. This guide is currently available for download for free on the FPInnovations website.

Introduction

The energy efficiency requirements for buildings are changing rapidly across Canada and the United States. Most new thermal insulation requirements for enclosures will be based on effective R-values by calculation, taking into consideration thermal bridging through structural framing, instead of the traditional requirements based on the nominal R-values of the insulation materials. In many climates and jurisdictions, the minimum thermal requirements in building codes will exceed the insulation capacities provided by the traditional wood-frame assemblies using 2x4 or 2x6 dimensional lumber. In addition, wood construction has been getting taller and expanding into new markets. For example, mostly for residential construction, 5- and 6-story construction has been permitted in several jurisdictions including California, Oregon, Washington, British Columbia, and Quebec. New building systems based on timber products, such as cross-laminated timber (CLT), and hybrid systems, such as the use of non-bearing wood-frame exterior walls (infill walls) in post and beam construction, have also emerged. Associated with all these new requirements, taller buildings, and new wood building systems, concerns may rise about how to build durable building enclosures, particularly under the new energy efficiency requirements.

In response to this FPInnovations recently published a "Guide for Designing Energy-Efficient Building Enclosures for Wood-Frame Multi-Unit Residential Buildings in Marine to Cold Climate Zones in North America" (Finch et al. 2013) (Figure 1), in collaboration with RDH Building Engineering Ltd., the Homeowner Protection Office, Branch of BC Housing (HPO), and the Canadian Wood Council (CWC). Several other organizations and professionals also contributed by providing peer review comments and other information, in addition to the partners and authors of this guide. This document is currently available for download for free on the FPInnovations website (http://www.fpinnovations.ca/ResearchProgram/AdvancedBuildingSystem/designing-energy-efficient-building-enclosures.pdf).

Based on the existing design and construction practices and relevant research, focusing on wood-based building enclosures of multi-unit residential buildings, this guide was intended to serve two major objectives: firstly to assist architects, engineers, designers, and builders in meeting the increasingly stringent energy efficiency requirements and improving the thermal performance; secondly to advance good design and construction practices to ensure the durable performance of the building enclosures that are insulated to higher levels than the traditional wood-frame construction. Figure 1 is a photograph of the cover page of this document. The design guidelines in this guide are targeted towards buildings in Marine to Very Cold Climate Zones (DOE/ASHRAE Climate Zones 5 through 7 and parts of Zone 4), as shown in Figure 2.

The guide applies building science fundamentals for moisture, air, and thermal management, design of energy-efficient and durable wall and roof assemblies, and building enclosure detailing for key interfaces. It builds on the 2011 Building Enclosure Design Guide for Wood-Frame Multi-Unit Residential Buildings (HPO 2011). It briefly summarizes the major thermal requirements within the 2011 National Energy Code of Canada for Buildings (NECB 2011), 2010 National Building Code of Canada update (NBC 2013), 2012 International Energy Conservation Code (ICC 2012), and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1–Energy Standard for Buildings Except Low-Rise Residential Buildings (ASHRAE Standard 90.1 2004, 2007, and 2010 versions).

This guide focuses on critical issues related to highly insulated assemblies including selection and proper placement of thermal insulation and other materials, calculation of effective thermal resistance, cladding attachment through exterior insulation, and detailed drawings for key enclosure interfaces. Additionally, whole-building energy efficiency, impacts of thermal bridging and fenestration, thermal mass impact of heavy timber construction, and thermal and hygrothermal performance simulations are also discussed within this guide.

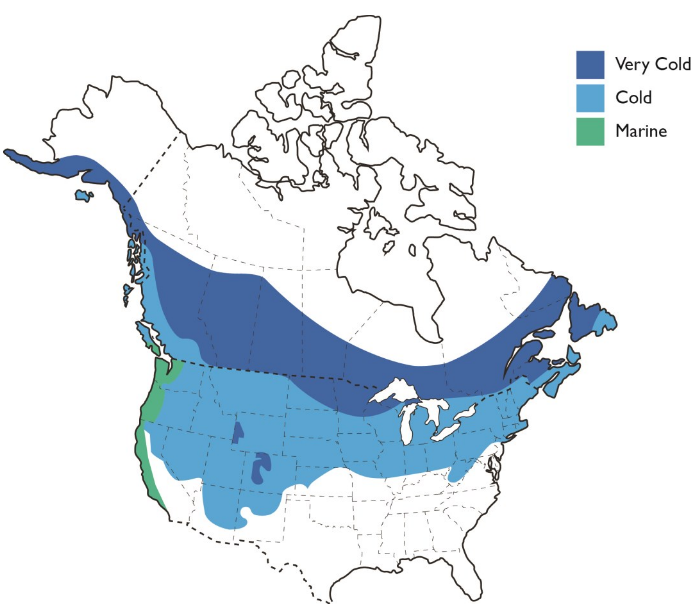


Figure 2. The Marine to Very Cold Climate Zones Discussed in the *Guide for Designing Energy-Efficient Building Enclosures*

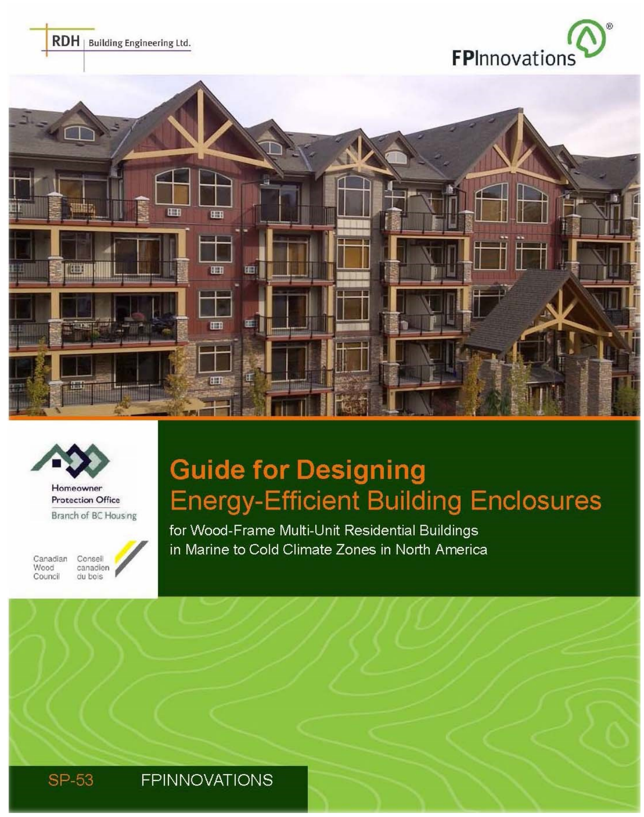
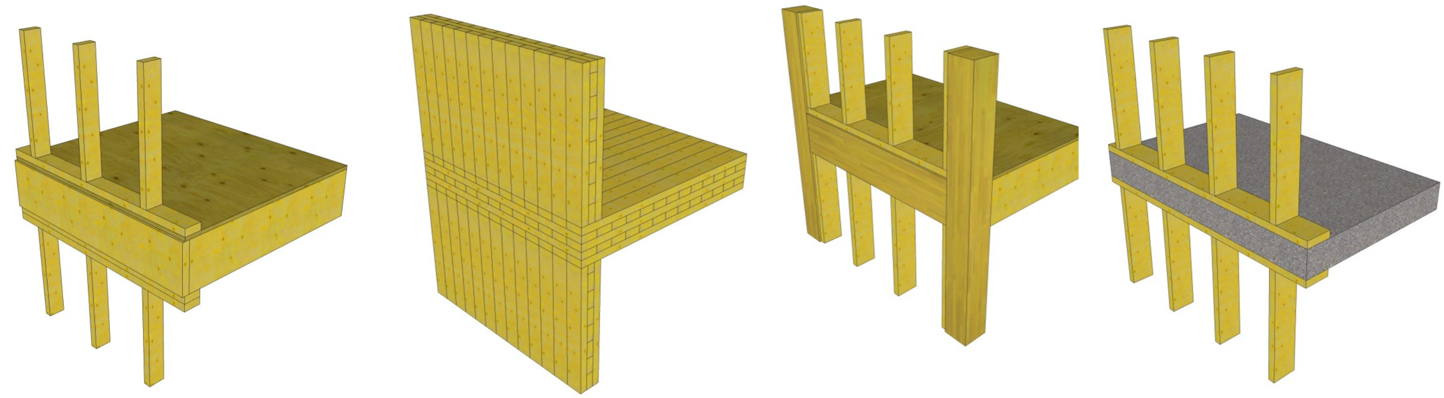


Figure 1. Cover of the *Guide for Designing Energy-Efficient Building Enclosures*

Structural Systems for Building Enclosures

This guide largely focuses on the building enclosure assembly design of wood platform frame construction, since it is a dominant construction type for low-rise buildings across Canada and the United States as well as 5- and 6-story construction in several jurisdictions. This construction type has a proven record of performance with much knowledge and experience existing in the design and construction communities.

From a thermal perspective, wood-frame building enclosures are inherently more efficient than steel frame, concrete, or masonry construction resulting from the much reduced thermal bridging through structural framing due to the much lower conductivity of wood products. But concerns may rise from designers when additional insulation is required for assemblies using 2x4 or 2x6 dimensional lumber to meet the minimum thermal requirements in building codes. Moreover, higher framing to insulation ratios, commonly seen at the lower levels of 5- and 6-story wood-frame buildings resulting from more stringent structural requirements, introduce more thermal bridging and demand more effective insulation. This guide pro-



(a) Platform Framing **(b) Mass Timber—CLT** **(c)Post and Beam Framing** **(d) Wood Frame Infill**

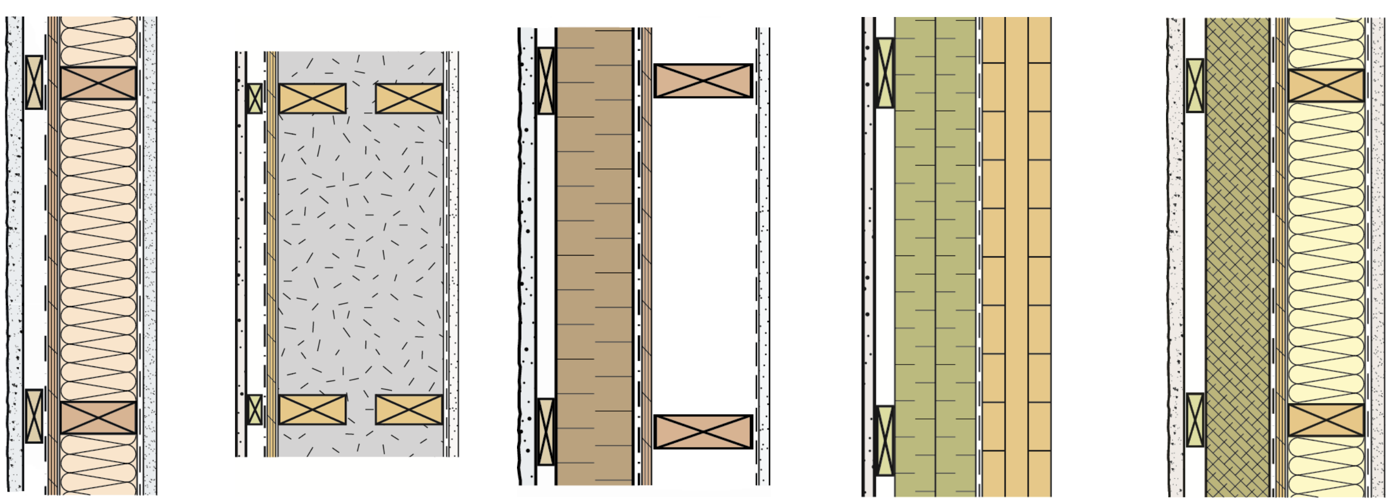
Figure 3. Building Enclosure Systems Discussed in *Guide for Designing Energy-Efficient Building Enclosures*

vides alternative assemblies that include insulation outside the framing spaces, such as exterior insulated and split-insulated assemblies, and deeper stud cavities, such as double-stud walls.

In addition to the traditional wood-frame construction, this guide includes information regarding thermal performance and detailing of enclosures based on engineered wood and mass timber systems. The CLT-related information is complementary to the two comprehensive Cross-Laminated Timber Handbooks, the Canadian Edition (FPInnovations 2011), and the US Edition (FPInnovations and Binational Softwood Lumber Council 2013) in terms of CLT building enclosure design, but goes further by providing two-dimensional and three-dimensional details for CLT assemblies. The guidelines provided are generally applicable to building enclosures based on other engineered timber or panel products, such as parallel strand lumber (PSL), laminated strand lumber (LSL), and laminated veneer lumber (LVL).

The guide also provides brief direction and details for wood infill wall applications in both wood post-and-beam and concrete structures. Wood-based infill wall systems have been quite commonly used in mid-rise and high-rise concrete buildings in Sweden and other Northern European countries. The major advantages of wood walls are related to improved thermal performance due to much reduced thermal bridging, less insulation and thinner walls (i.e. increased indoor space), and lower costs to meet thermal insulation requirements in comparison with steel-stud walls. Wood infill walls are gaining acceptance in North America typically through alternative solutions to satisfy the fire safety requirements.

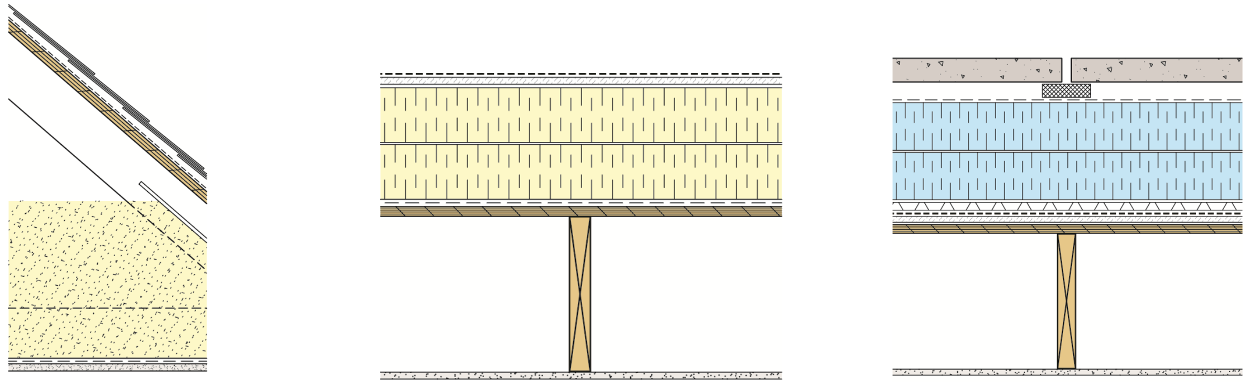
Figure 3 are illustrations of the four types of enclosure systems covered in this guide.



2x6 Stud Walls **Double Stud Walls** **2x4(or 2x6) Stud Wall** **CLT/Mass Timbers** **2x4 (or 2x6) Stud Wall**

(a)Interior-Insulated Wall Assemblies **(b) Exterior-Insulated Wall Assemblies** **(c)Split-Insulated Wall Assembly**

Figure 4. Options for Placement of Insulation Within Thermally Efficient Above-Grade Wall Assemblies



(a) Interior-Insulated Pitched Roof (b) Low Slope Roof: Conventionally Insulated (c) Low Slope Roof: Inverted

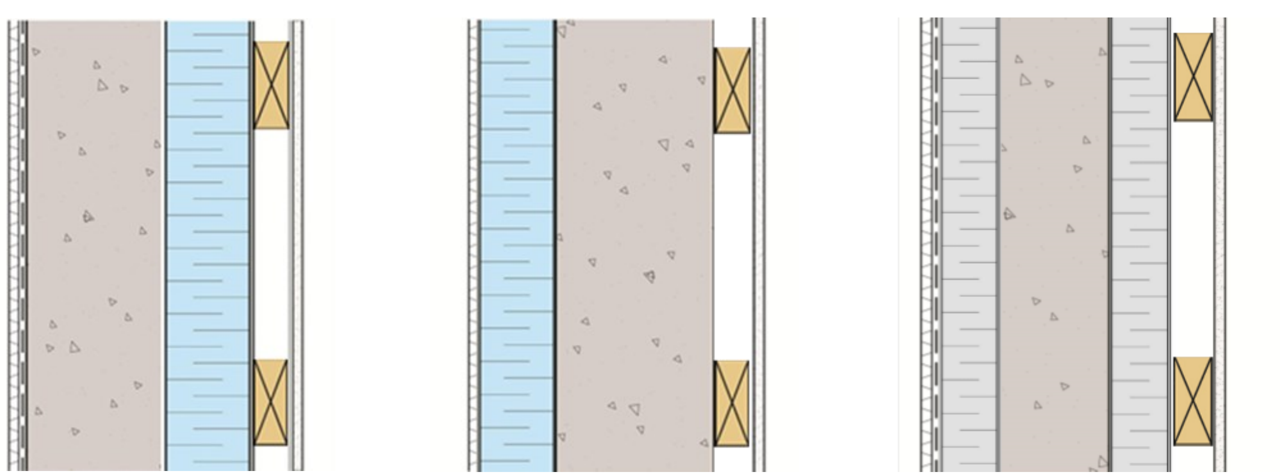
Figure 5. Options for Placement of Insulation Within Selected Thermally Efficient Roof and Roof Deck Assemblies

Thermal Insulation and Enclosure Design

Since North American energy efficiency-related codes and standards target greater insulation levels of opaque enclosure assemblies, this guide elaborates on thermal insulation strategies and selection and placement of materials to achieve both thermal efficiency and durability. Detailed guidelines are provided for the design of above-grade wood-based walls and roofs as well as below-grade concrete walls to reduce thermal bridging, achieve effective insulation, and prevent water penetration and vapor condensation.

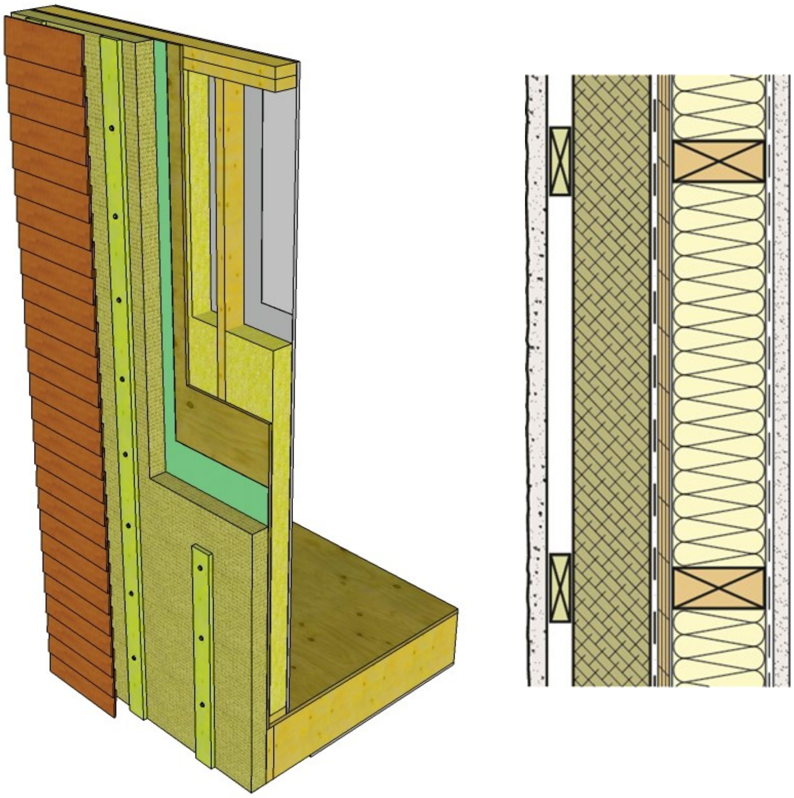
The general thermal insulation strategies for above-grade exterior walls are illustrated in Figure 4, including interior-insulated (including double-stud), exterior-insulated and split-insulated wall assemblies. The major insulation strategies for roofs are summarized in Figure 5, including interior-insulated pitched roofs (including roofs with raised heel truss), and low-slope roofs with conventional roofing systems or inverted roof systems. In the guide, details about pitched roofs with exterior rigid insulation are also provided. The general insulation options for below-grade walls that can be used for wood buildings are illustrated in Figure 6.

The selection and placement of insulation as well as other materials in the building enclosure depends on a variety of factors including local regulations, traditional practices, material and labor costs, material availability, thermal performance, and moisture tolerance. In terms of insulation material alone, there are a range of products available on the market with very different properties, such as thermal performance, vapor permeability, and air tightness, as well as installation methods. The guide provides basic and generic properties of the commonly used insulation products related to use in both framing cavities and as continuous insulation outside the framing members, when used in above-grade walls, below-grade walls, or roofs. For highly-insulated wood-frame assemblies, controlling rain penetration, air leak-



(a) Interior-Insulated Wall (b) Exterior-Insulated Wall (c) Interior– and Exterior– Insulated Wall

Figure 6. Options for Placement of Insulation Within Thermally Efficient Below-Grade Wall Assemblies



EXTERIOR

- Cladding
- Airspace (ventilated)
- 1x3 wood strapping, screwed through Insulation
- Rigid, mineral-fibre insulation (thickness to meet R-value requirement)
- Vapour-permeable sheathing membrane
- Sheathing (plywood or OSB)
- 2x4 or 2x6 wood framing with batt insulation
- Polyethylene film (cold climates only)
- Gypsum board and paint

INTERIOR

Figure 7. Split-Insulated Wood-Frame Wall Assembly with Exterior Rigid Mineral-Fiber Insulation

age, and vapor condensation becomes more critically important due to the deduced drying capacity. The selection of a suitable insulation material and its location within the assembly, detailing for good airtightness, and use of appropriate vapor control are all important measures to minimize interstitial vapor condensation.

Chapter 4 summarizes design details of representative building enclosures assemblies, including schematics and key aspects of rain management (water-shedding surface and water-resistive barrier), air barrier, thermal insulation, and vapor flow control. Figures7-11 are diagrams of the example schematics provided in the document. This chapter also provides a series of tables listing effective R-values for various wall and roof assemblies, taking into consideration the cladding attachment methods.

Chapter 5 provides two-dimensional colored CAD drawings for detailing at critical enclosure interfaces, such as bases of wall/foundation, floor edges, windows, roof/wall interfaces, balcony/wall interfaces, and service penetrations. Three-dimensional sequencing schematics are also provided for window installation within traditional framing, double-stud framing, split-insulated walls, and CLT construction.

Concluding Remarks

The guide was developed to assist architects, engineers, designers, and builders in designing and building durable and energy efficient wood-based building enclosures and to meet the new energy efficiency requirements for buildings. The guidelines provided are expected to be updated when new knowledge and experience becomes available for highly insulated building enclosure assemblies.

Acknowledgments:

Funding for this project was provided by Natural Resources Canada (NRCan) through the Transformative Technologies Program under the contribution agreement between NRCan and FPInnovations. The Homeowner Protection Office, Branch of BC Housing (HPO), and the Canadian Wood Council provided both financial support and in-kind contribution. FPInnovations and RDH Building Engineering also provided in-kind contribution.

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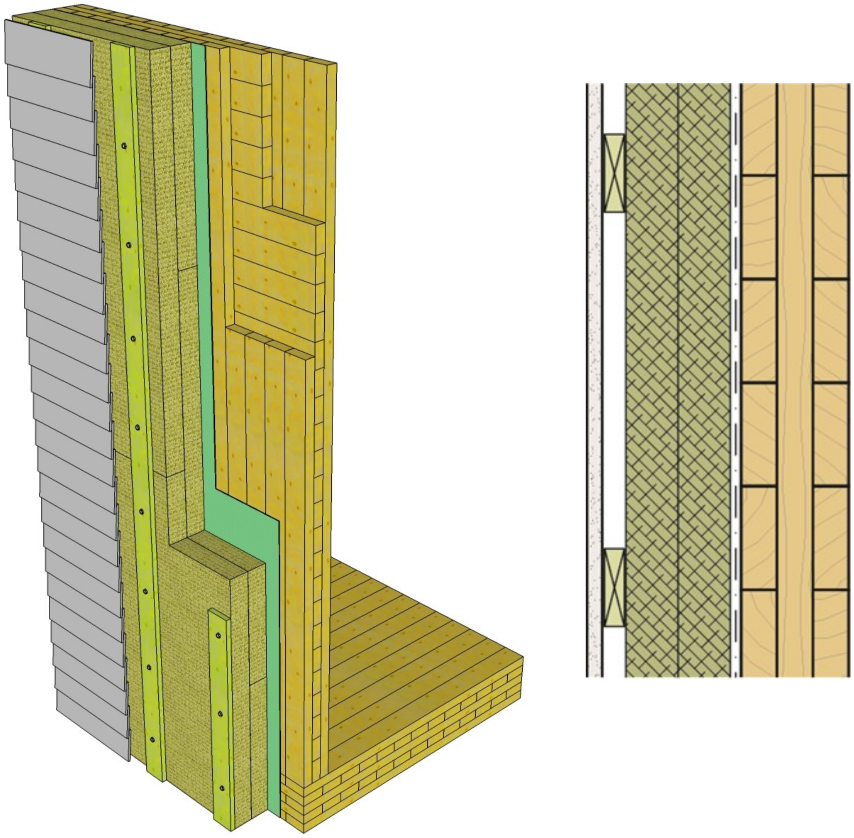

EXTERIOR

- Cladding
- Airspace
- 1x3 wood strapping, screwed through Insulation
- Rigid mineral-fibre Insulation
- Vapour-permeable sheathing membrane
- CLT panel
- Furring and gypsum board (if required for aesthetics or fire code)

Figure 8. Exterior-Insulated CLT Wall Assembly

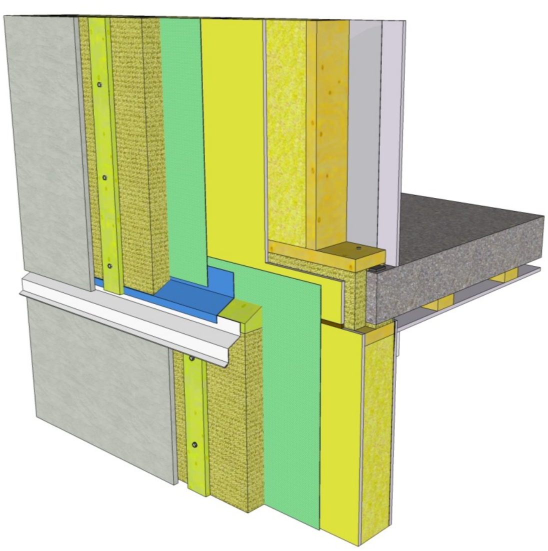

Figure 9. Exterior-Insulated Wood-Frame Infill Wall for Concrete Structures

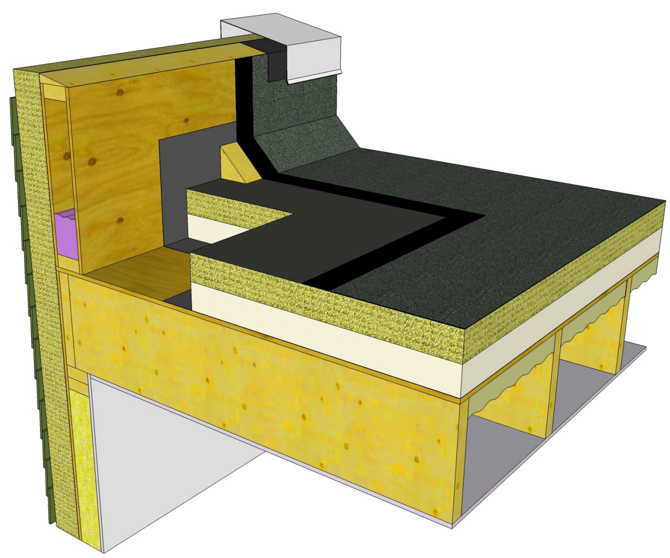

Figure 10. Low Slope Roof With Conventional Roof Assembly

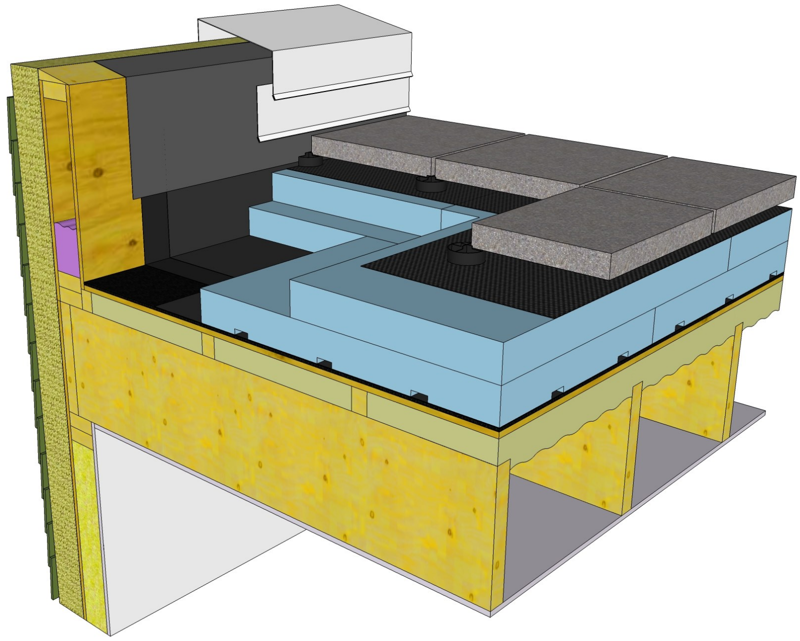

Figure 11. Low Slope Roof With Inverted (Protected Membrane) Roof Assembly

standards-research--technology/standards—guidelines.

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Moisture in Crawl Spaces

Anton TenWolde, and Samuel V. Glass, Ph.D.

Abstract

Crawl space foundations can be designed and built to avoid moisture problems. In this article we provide a brief overview of crawl spaces with emphasis on the physics of moisture. We review trends that have been observed in the research literature and summarize current recommendations for moisture control in crawl spaces.

Introduction

What does it take to design and construct a crawl space that is free of moisture problems? Crawl spaces are often historically and anecdotally associated with dampness more so than other foundation types. This article provides an overview of design factors that are critical for avoiding moisture problems in crawl spaces.

A crawl space is defined by the Merriam-Webster dictionary as "a shallow unfinished space beneath the first floor or under the roof of a building especially for access to plumbing or wiring." For the purposes of this article, we focus on foundations and exclude under-roof spaces. Britton (1948) defined a crawl space as "that enclosed space (or spaces) under the first floor of a building where there is no basement or occupancy and the first floor is some distance above the surface of the ground."

For the purposes of this article, we find it useful to distinguish three different ways of building a crawl space.

1. Open crawl space: pier-and-beam construction where the perimeter is substantially open to airflow (Figure 1)
2. Wall-vented crawl space: continuous perimeter wall that includes vents to the outside (Figure 2)
3. Closed crawl space: continuous perimeter wall with no vents to the outside (Figure 3)

Crawl space foundations primarily originated in the southern United States, where homes were commonly built on pier foundations (Rose 1994). These pier foundations were typically fully open to the outside, or had minimal skirting that allowed virtually unrestricted air movement. During World War II "basementless" houses

Figure 1. Example of an Open Crawl Space with a Pier Foundation.

[USDA Forest Service Forest Products Laboratory]

began to be constructed in the northern United States, and this was accompanied by the first requirements for minimum vent openings in crawl spaces, promulgated by the Federal Housing Administration (FHA 1942, Rose 1994). The requirements were intended to prevent moisture problems in crawl spaces, but there appears to be no technical basis for these requirements in the literature (Rose 1994).

Figure 2. Example of a Wall-Vented Crawl Space with Ground Cover.

[USDA Forest Service Forest Products Laboratory]

Recommendations to limit water evaporation from the ground by employing a vapor-resistant ground cover first begin to appear in 1949 (Britton 1949). But as early as 1946, Diller (1946) reported that ground covers significantly lowered measured moisture content in the wood floor members in the crawl space, whether the vents were open or closed. Later research affirmed the effectiveness of ground covers (Diller 1953, Moses 1954, Amburgey and French 1971, Dutt et al. 1988, Quarles 1989, Flynn et al. 1994, Stiles and Custer 1994). However, findings were sometimes confounded by opening or closing of crawl space vents at the same time that ground covers were installed or removed (e.g. Moses and Scheffer 1962, Duff 1978). Curiously, vents were adopted as a requirement in the building codes, while ground covers were not, even though the technical evidence for the benefits from the latter is much stronger.

A number of studies in various climates have shown that closed crawl spaces (without vents to the outside) can remain relatively dry with a ground cover (Duff 1978, 1980; Moody et al. 1985; Dutt et al. 1988; Quarles 1989; Samuelson 1994; Stiles and Custer 1994; Davis and Dastur 2004). These studies generally observed more stable humidity and moisture conditions in the closed crawl spaces compared with wall-vented crawl spaces. The reasons for this are discussed below.

Figure 3. Example of a Closed Crawl Space with Ground Cover.

[Advanced Energy, Raleigh, NC]

The Physics of Moisture in Crawl Spaces

Moisture conditions in crawl spaces are determined by the balance between moisture entering the crawlspace, moisture removed, and moisture stored in various hygroscopic materials in the crawlspace, such as wood and concrete. Although moisture storage in materials in the crawlspace can provide some moderation of wide swings in moisture conditions, moisture storage is generally not sufficient to affect long term conditions. Because our concern is avoiding excessive moisture accumulation over the long-term, we therefore focus on the remaining factors in this equation: moisture entering and leaving the crawl space.

Moisture Sources

The main sources of water in the liquid or vapor phase are ground water or rain water intrusion, evaporation from the soil, and water vapor carried in with ventilation air. In some cases, water leaks from broken water pipes have been found as major contributors. The amount of water entering the crawl space can be very large, dominating the equation, and therefore limiting water entry should be the first priority. This can be accomplished with site grading, appropriate location and drainage of downspouts, and foundation drainage.

Evaporation from wet soil can be a significant contributor of water vapor. TenWolde and Pilon (2007) estimate that evaporation rates from wet soil can be as high as 0.2 kg/(m^2·h) (0.05 lb/(ft^2·h)), but greatly depend on the temperature of the soil, the humidity of the air in the crawlspace, and the amount of heat available to evaporate the water. Trethowen (1988, 1994) measured vapor release rates from soil in crawlspaces and reported an average release rate of 0.4 kg/(m^2·da) (0.08 lb/(ft^2·da)) from bare soil. This translates into around 0.017 kg/(m^2·h) (0.0034 lb/(ft^2·h)), which is less than 10% of the maximum theoretical rate cited by TenWolde and Pilon. Trethowen found that the evaporation rate varied greatly with soil temperature; the rate decreased substantially as soil temperature decreased. He also found that sources of heat in the crawl space, such as heating ducts or a furnace, can greatly increase the rate of evaporation. Of course, this rate can be drastically lowered by installing a vapor barrier (ground cover) over the soil.

Moisture Removal

Moisture removal can occur by ventilation if outdoor air contains less moisture than the air in the crawl space. A simple calculation is given here for the sake of illustration. Assuming a wall-vented crawl space with no ground cover and an evaporation rate from the soil of 0.4 kg/(m^2·da) (0.08 lb/(ft^2·da)), a fair amount of ventilation is needed. If the incoming ventilation air is at 21°C (70°F) and 50% relative humidity (RH), and the crawl space is at the same temperature, the minimum amount of air needed to maintain the crawl space air below 80% RH is on the order of 100 L/s (about 200 ft^3/min) for every 100 m^2 (about 1100 ft^2) of crawlspace floor area. Providing vents in the perimeter wall does not guarantee significant, reliable ventilation. The actual amount of ventilation with outdoor air depends on wind conditions, location of the vents, location and surroundings of the building, obstructions in front of the vents, and other factors.

Temperature Effects

If the dew point of the ventilation air is above the temperature of the soil in the crawl space, the air is incapable of removing moisture, and instead is a source of moisture to the crawl space. This can become an issue during humid weather in spring when soil temperatures remain cool. During summer the outdoor dew point can also exceed soil temperatures. This situation is not limited to hot-humid climates; it also commonly occurs in northern climates during summer. Table 1 lists mean dew point temperatures for the month of July in 30 U.S. locations.

An abundance of ventilation with outdoor air raises the crawl space temperature closer to that of the outdoors. Air exchange is typically much higher in open crawl spaces than in wall-vented crawl spaces. This is one reason why the old-fashioned open pier foundation with ample ventilation worked well in the past, and returning to that design is another option (see Figure 1). Temperature and absolute humidity levels in open crawl spaces generally track outdoor levels fairly closely (Glass et al. 2010). In contrast, temperature levels in wall-vented crawl spaces tend to be cooler than outdoors during warm weather. This means that during summer, relative humidity levels in open crawl spaces are typically lower than in wall-vented crawl spaces.

The majority of contemporary buildings are air-conditioned. Indoor cooling set points are frequently close to (sometimes below) outdoor dew point temperatures. In air-conditioned buildings, outdoor air can thus pose a condensation risk to subfloor sheathing or decking. In open crawl spaces and wall-vented crawl spaces, this risk may be mitigated by insulating the floor with foam insulation of low vapor permeance (Glass et al. 2010, Lstiburek 2008), or by installing a vapor retarder at the underside of vapor-permeable floor insulation (Verrall 1962). Air tightness is key in such cases so that water vapor is not carried by air leakage into the floor assembly.

Closed crawl spaces (see Figure 3) are designed with the intent of separating the crawl space from the outdoors. This type of construction requires a ground cover to minimize entry of soil moisture, air sealing at the perimeter, and either introduction of conditioned air into the crawl space or direct dehumidification to control humidity levels in the crawl space (ground covers and air sealing minimize moisture entry but may not be 100% effective).

Table 1. July Mean Dew Point Temperatures for 30 U.S. Locations From 1984 to 2012 (NCDC 2012)

Location	°F	°C
Salt Lake City, UT	49.8	9.9
Denver, CO	52.4	11.3
Seattle, WA	53.8	12.1
San Francisco, CA	54.0	12.2
Portland, OR	55.6	13.1
Phoenix, AZ	58.7	14.8
Los Angeles, CA	61.4	16.3
Minneapolis, MN	62.3	16.8
Boston, MA	62.7	17.1
Chicago, IL	63.4	17.4
New York, NY	65.6	18.7
Philadelphia, PA	66.4	19.1
Washington, DC	66.7	19.3
Baltimore, MD	66.8	19.3
Louisville, KY	67.9	19.9
St. Louis, MO	68.1	20.1
Kansas City, MO	68.2	20.1
Atlanta, GA	69.3	20.7
Dallas, TX	69.8	21.0
Norfolk, VA	70.4	21.3
Memphis, TN	71.4	21.9
Wilmington, NC	72.8	22.7
Savannah, GA	72.9	22.7
Tallahassee, FL	73.0	22.8
Orlando, FL	73.5	23.1
Charleston, SC	73.6	23.1
Houston, TX	73.7	23.2
Miami, FL	74.3	23.5
New Orleans, LA	74.4	23.6
Corpus Christi, TX	74.9	23.8

Measured Moisture Conditions

In a review of measured data on in-service moisture and temperature conditions in wood-frame buildings, Glass and TenWolde (2007) observed that high moisture content (MC) values in wood floor structural members (joists, beams, sill plates, subfloor sheathing) have been measured at various times of the year, in all climate zones in the United States. Some of these readings were well over 20% MC, which is generally recognized as the moisture content at which we become concerned about mold and decay. On the basis of these historical data Glass and TenWolde (2007) make the following specific observations:

- The most extreme measured moisture contents in wood structural members above crawlspace foundations occur when the ground is not covered with a vapor-resistant ground cover. This effect is magnified for sites with poor drainage.
- Two different seasonal trends have been observed for crawlspaces:

1. Wood moisture content reached a maximum in winter and minimum in summer. This trend was observed in studies prior to ca. 1955 in crawlspaces without a ground cover in both mixed-humid and cold climates. The most likely explanation is that when the crawlspace vents either were lacking or were closed during winter, the uncovered soil supplied moisture that condensed on the coldest wood members in the crawlspace. During winter months, the coldest members are the sill plates, rim joists, and floor joists near the exterior. It should be noted that the buildings were not air-conditioned during the summer, and the floor framing therefore was probably warmer than the crawlspace soil (or below-grade portions of the crawlspace walls), for most of the time during summer months.
2. Wood moisture content peaked in summer, with a minimum in winter. This trend has been reported in hot-humid and mixed-humid climates in all studies conducted since ca. 1955 in which seasonal trends were investigated. These studies included various types of crawlspaces (both covered/uncovered and vented/closed). In many of these studies, the living space above the crawlspace was either known to be, or was probably air-conditioned during the summer. The major source of crawlspace moisture in these studies was either warm, humid outdoor air or moisture evaporating from the soil. In summer, the floor members can be cooler than the outdoor air (sometimes cooler than the outdoor dew point temperature), especially when the building is air-conditioned. Drying would have occurred during fall and winter because outdoor air would contain less water vapor and cooler soil would have a slower rate of evaporation.

Recommendations

The following recommendations for moisture control in crawl spaces are mostly based on the 2005 ASHRAE Handbook, Chapter 24, Thermal and Moisture Control in Insulated Assemblies—Applications (ASHRAE 2005).

Accessibility

One of the principle reasons that problems occur in crawl spaces is that owners or occupants do not regularly inspect the crawl space. By inspecting regularly, problems with standing water or plumbing leaks are discovered and corrected sooner, hopefully before major damage occurs. Inspection can also uncover problems with water entry from outside, allowing timely corrective action. The crawlspace therefore needs to be easily accessible, well illuminated, and clean. Although a minimum clearance of 18 inches (0.46 m) between the soil and the bottom of the floor joists is often recommended, it is advisable to increase this to 40 inches (1 m) for easier access.

Water Entry

The soil in the crawl space should be kept as dry as possible, and therefore water entry into the crawl space should be prevented. It is recommended that the crawl space floor level not be below the exterior grade. Proper site drainage is also critical. Gutters and downspouts should carry rain water away from the foundation, and the site should be sloped away from the foundation to allow water to drain away. If this is not possible, berms, retaining walls, and other means may be used to guide the water around and away from the building. In case of high ground water levels, installing sump pumps may be useful.

If a building is to be constructed on a site with poor grading and drainage or where the water table is close to the surface, an open pier foundation with substantial grade clearance would be the most viable option. With wet soils, capillary rise through stem walls may be an issue. This issue is largely side-stepped with open-pier foundations.

Ground cover

Measurements have consistently shown that ground covers can significantly lower moisture conditions in the crawl space. Recommendations usually call for ground cover material with a water vapor permeance of no more than 1 perm, and the material must be strong enough to withstand foot and knee traffic. Polyethylene with a minimum thickness of 6 mil (0.006 in, 0.15 mm) is commonly used. A concrete slab may be poured over the ground cover to keep out rodents. Debris must be removed and the soil leveled before installing the ground cover. The seams of the ground cover should be lapped 4 to 6 in (100 to 150 mm), and no sealing is required.

Open pier-and-beam construction generally does not require a ground cover because the amount of air flow under the floor is sufficient to carry away excess moisture (Glass et al. 2010).

Vents

The 2006 International Residential Code (IRC) (ICC 2006) contains a standard requirement for minimum vent openings of 1 ft^2 per 150 ft^2 of crawlspace floor area (1 m^2/150 m^2). As noted earlier, there is no known technical basis for these requirements, and providing vents does not guarantee actual airflow. Research has also shown that with warm humid outdoor conditions, providing 1/150 vents can be counterproductive. However, the 2006 IRC does allow omitting the vents in a crawl space with perimeter insulation if a) a ground cover is installed (sealed and taped), with the cover extending 6 inches (150 mm) up the side walls; and b) the crawlspace has a continuously operated exhaust fan, or conditioned air is supplied to the crawl space, or the crawl space is used as a plenum.

If local codes require vents or vents are desired, one should consider going well beyond the minimum requirement of 1/150 to ensure that there is enough air movement to raise the crawl space temperature above the dew point of the outside air during summer.

Other Considerations

From the perspective of energy use, it is best not to locate ducts for heating and cooling in unconditioned spaces. Locating ducts in a crawl space with vents in the perimeter walls will also complicate air sealing and insulating of the floor over the crawlspace. If it is necessary to locate ducts in a crawl space that is vented with outdoor air, air sealing and insulating those ducts is very important. Poorly sealed supply ducts often fail to deliver adequate conditioned air to locations where it is desired. Poorly sealed return ducts may introduce crawlspace air into the living space. If the crawlspace air is humid or contains contaminants (soil gases, mold spores, mold metabolites, or volatile chemicals), the humidity or the contaminants (or both) will be introduced into the living space. Properly insulating the ducts limits energy losses and reduces the chance of condensation on the ducts when the air-conditioning is running. If it is necessary to locate ducts in a crawl space, it may be viable to construct a closed crawlspace and to insulate the walls (Davis and Dastur 2004). This, of course, assumes that water entry into the crawlspace is controlled, that there is a functioning soil cover, and that volatile substances (e.g., gasoline or gasoline-powered tools) are not stored in the crawlspace.

It is of paramount importance to vent clothes dryers outdoors (not into the crawlspace), and to repair any leaking water pipes.

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Hygrothermal Simulation: A Tool for Building Envelope Design Analysis

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Abstract

Is it possible to gauge the risk of moisture problems while designing the building envelope? This article provides a brief introduction to computer-based hygrothermal (heat and moisture) simulation, shows how simulation can be useful as a design tool, and points out a number of important considerations regarding model inputs and limitations. Hygrothermal simulation allows a designer to predict the moisture and temperature conditions that might occur within a building envelope assembly over time. This type of analysis can improve the understanding of how the building envelope responds to the interior and exterior environment and can help identify potential moisture performance problems. The article briefly discusses the relationship between hygrothermal simulations and ASHRAE Standard 160-2009, *Criteria for Moisture-Control Design Analysis in Buildings* (ASHRAE 2009). The article concludes with simulation examples using wood-frame construction and cross-laminated timber construction to demonstrate the usefulness of hygrothermal analysis in the design of wood buildings.

Introduction

Avoiding moisture problems is a key consideration in building envelope design. Dampness in buildings has been linked to health problems and is the top category for construction litigation claims. Although moisture problems are often a result of improper construction, building operation, or maintenance, some moisture problems stem from poor design, and fixing moisture problems is much more expensive after construction than during the design process. What tools are available to designers to avoid such problems?

Moisture performance is a multi-faceted issue; in a qualitative sense, desirable performance is characterized by a balance between moisture entering and leaving a building component without resulting in damage or mold growth. This means limiting moisture accumulation as well as providing some degree of "tolerance" such that assemblies have the ability to dry out if wetting occurs (either during construction or service life). But how much moisture tolerance is needed? To design for this balance, a *quantitative* estimate of the rates of wetting and drying is needed. Hygrothermal analysis can provide such an estimate and takes moisture performance to a *quantitative* level.

Hygrothermal simulation allows a designer to predict the moisture and temperature conditions that might occur within a building envelope assembly over time. Such analysis can improve the understanding of how the building envelope responds to the interior and exterior environment and can help identify potential moisture performance problems. Although hygrothermal simulation is commonly used in research and forensic investigations, this article focuses on design analysis. The purpose of this article is to give the reader a sense of what can be gained from hygrothermal simulation as a design tool, to alert the reader to a number of important considerations regarding model inputs and limitations, and to illustrate the usefulness of hygrothermal simulation with brief examples for wood-based building envelopes.

When Is Hygrothermal Simulation Necessary?

Judgment is required to determine whether a particular design requires hygrothermal analysis. There may be no need for analysis when ample experience exists with a given type of building envelope assembly in a given location. However, many aspects of design and construction are changing: energy code requirements, green building standards, new building materials and systems, and new methods of construction. It is important to consider how these changes affect moisture performance. Ideally the designer would have information on the performance of a proposed assembly based on testing or field experience; however, such information is often lacking.

Hygrothermal analysis methods can vary widely in the physical phenomena that are included. On one end of the spectrum are simple steady-state models, such as the traditional dew point method, that include only heat conduction and vapor diffusion with constant material properties; on the other end are sophisticated computer models that include transient heat, vapor, liquid, and air transfer in as many as three dimensions, with variable material properties and detailed descriptions of phenomena such as airflow and wind-driven rain.

The dew point method and its limitations are described in the ASHRAE Handbook—Fundamentals (ASHRAE 2013) and TenWolde and Bomberg (2009). The method relies on steady-state heat flow and vapor diffusion calculations to determine whether the vapor pressure exceeds the saturation vapor pressure at any location within the assembly. The dew point method has many significant limitations. Moisture storage in hygroscopic materials such as wood is neglected, and all moisture transfer mechanisms other than vapor diffusion are excluded, even though those mechanisms are known to dominate moisture transfer in many cases. That is, the method does not address wind-driven rain absorption by cladding materials, capillary water transport, heat and moisture transfer by air movement, effects of solar radiation, or the dependence of material properties on local temperature and moisture content.

Over the past three decades, many detailed computer models have been developed to simulate temperature and moisture conditions in building envelope assemblies over time. Such models perform transient calculations, typically reporting hourly values. Further information on some advanced hygrothermal models can be found in Hens (1996) and ASTM Manual 40 (Trechsel 2001). Commonly used software packages include WUFI Pro, hygIRC, and Delphin. It should be noted that use of hygrothermal computer software requires training and experience in selection of input values and interpretation of results.

Hygrothermal Loads

The important concept of "load" is used in hygrothermal analysis in the sense of a burden or demand on the building; the response of the building to the loads can be analyzed, and the performance can be judged to be acceptable or unacceptable (TenWolde 2011). Hygrothermal loads are analogous to loads considered in structural analysis (e.g., gravity and lateral loads) and to heating and cooling (sensible and latent) loads in mechanical system design. Hygrothermal loads include initial moisture levels in building materials; indoor temperature and humidity levels; outdoor conditions such as temperature, humidity, wind, rain, and solar radiation; and air pressure differences across the building envelope.

Although hygrothermal simulation tools have become more sophisticated and able to accurately predict moisture and temperature conditions when compared with validation experiments, relatively little attention has been paid to the choice of appropriate inputs and loads for design purposes. This may not be an issue when using these tools in forensics to analyze a failure of an existing building because only the data for conditions during the period before the failure are needed (though obtaining accurate and sufficient data is difficult enough). However, the choice of appropriate input values is even more uncertain when the analysis is used for design purposes before the building has been built and before actual loads can be measured. These considerations suggested a need for a standardized approach to establish moisture design loads.

ASHRAE Standard 160

In January 2009, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) published a new standard, ANSI/ASHRAE Standard 160-2009, entitled *Criteria for Moisture-Control Design Analysis in Buildings* (ASHRAE 2009). Work on the standard began in 1996 and arose from the increased use of computer-based hygrothermal analysis tools and the concerns discussed above.

Another reason for creating this standard is that many recommendations and rules for moisture control are not based on a set of consistent underlying assumptions. The need for various moisture control strategies or design features often depends on what indoor or outdoor conditions are assumed. For instance, a computer analysis by Tsongas et al. (1995) of moisture accumulation in a wood frame wall in Madison, Wisconsin, showed that the need for including a vapor retarder in the design completely depended on the selection of indoor humidity. Many other studies have consistently shown that simulation results can be rather sensitive to the assumed loads (Ojanen and Kumaran 1992, TenWolde and Walker 2001, Karagiozis et al. 2007). The level of indoor humidity is equally important when considering the risk of condensation on windows, the risk of mold growth on wall surfaces, or the need for attic ventilation. Thus, the choice of input values for a design analysis is critical. Whether a design analysis will show acceptable or unacceptable performance of a particular design or moisture control strategy largely depends on the design loads operating on the building.

It is widely accepted that structural building design should be based on reasonable assumptions for structural design loads. To the extent feasible, ASHRAE Standard 160 introduces an analogous approach for moisture design. As with structural design loads, moisture design loads should be more severe than average loads. An international consensus has emerged that moisture design analysis should be based on loads that will not be exceeded 90% of the time. ASHRAE Standard 160 has adopted this approach whenever feasible.

TenWolde (2001) showed how the use of a moisture design standard such as ASHRAE Standard 160 might have alerted manufactured home builders to the potential of widespread decay of plywood sheathing that occurred in the mid-1980s in a group of manufactured homes in the Midwest. The article also shows how the use of the standard could have led to the solution and prevention of problems that occurred and might have circumvented a lot of the disagreements and litigation that took place following the discovery of the building failures.

In summary, the standard is intended to bring moisture control out of the realm of purely prescriptive measures and turn building moisture design analysis into a performance-based procedure, with the potential for greater flexibility and a better ability to incorporate new designs and building materials. In addition to uniformity of design assumptions, the standard also seeks to make the moisture design analysis procedure more transparent by requiring documentation of the assumptions, material properties used, and other choices made for the analysis. A recent summary of the standard was written by TenWolde (2011). Certain key aspects of the standard are discussed in the following sections. ASHRAE is continuing to make improvements and changes to the standard. Already three major changes (Addenda a, b, and c) have been published since the standard was published in 2009, and more will undoubtedly follow. These Addenda can be downloaded free of charge from www.ashrae.org.

Modeling Considerations

Building Envelope Assembly

The first step in a typical hygrothermal analysis is to define the assembly (i.e., an exterior wall, roof, or other type), its orientation, and its boundaries. This typically involves simplification into a one- or two-dimensional representation. Figure 1 shows a wood-frame wall assembly that will be analyzed as an example using one dimension, corresponding to a line through the insulated cavity. The various material layers are identified in the figure. Similarly, Figure 2 shows an example of a cross-laminated timber (CLT) wall assembly that is also modeled in one dimension. Some cases may require use of two dimensions, such as corners, roof-wall intersections, and floor-wall intersections.

Physical Phenomena and Material Properties

Transient hygrothermal models generally include coupled heat and moisture transfer. At the material level, a number of properties can be specified, such as thickness, bulk density, specific heat (heat capacity), thermal conductivity, moisture storage (sorption and suction isotherms), vapor permeance or permeability, liquid water diffusivity or conductivity, and possibly porosity, capillary saturation, maximum saturation, and airflow permeability. Certain properties may be specified as functions of moisture content (or relative humidity) and temperature (e.g., vapor permeability, thermal conductivity). Models generally include heat and moisture transfer coefficients for the interior and exterior surfaces as well as short-wave (solar) radiation absorptivity and long-wave (infrared) radiation emissivity.

Most models typically do not include airflow, though there are exceptions. Some models include the effect of cladding ventilation, which can be an important drying mechanism. Air leakage through insulated building envelope assemblies can be an important moisture transfer mechanism, especially for lightweight wood-frame cavities with low-density insulation (Straube and Burnett 2005, Glass and TenWolde 2007). Simulating air leakage in a realistic manner is difficult because the flow paths through building envelope assemblies are three-dimensional and difficult to define, and appropriate design air pressure boundary conditions are not easily established. Nevertheless, simplified models have been developed that can be useful for comparing relative performance of different assemblies. In such models, deposition of water vapor carried by air leakage is represented by a moisture source at a selected location in the assembly. The idea is that inclusion of the effect of air flow, even in such a simplified form, provides an extra safety factor in the design.

Initial Moisture Conditions

Some building materials, such as concrete, wet-spray cellulose insulation, and wood, may contain large amounts of moisture at the time of enclosure. Little quantitative information is available, and actual conditions likely vary substantially. ASHRAE Standard 160 accounts for this initial moisture load by prescribing high initial moisture contents for those materials, unless specific plans have been included in the construction cycle to dissipate

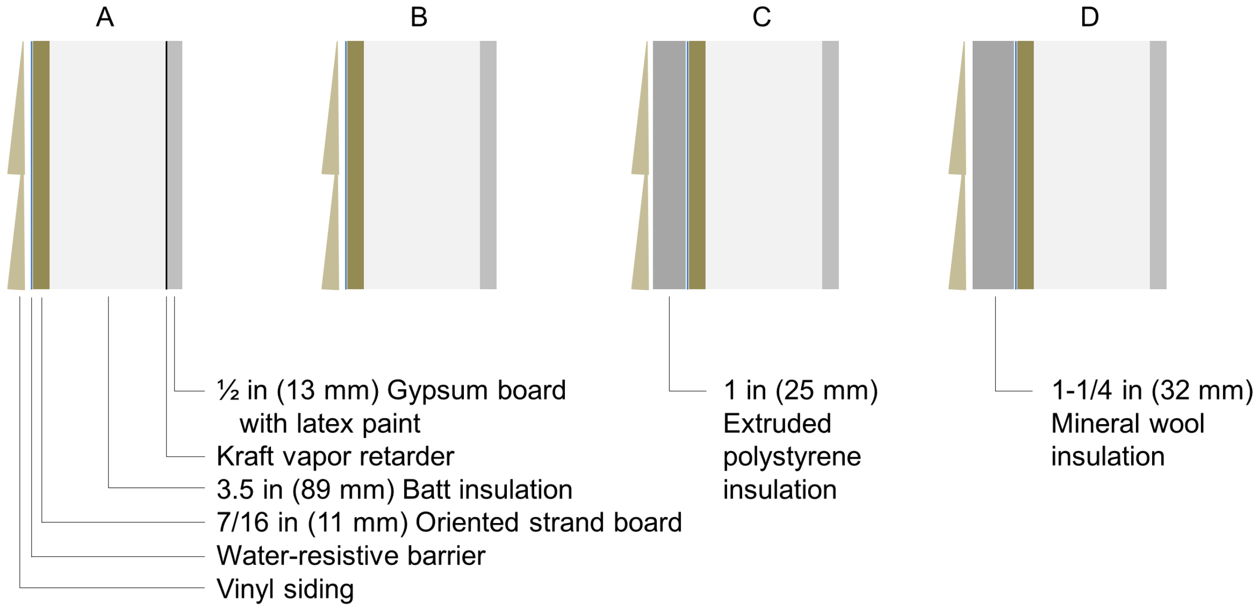

Figure 1. Example Wood-Frame Wall Assemblies.

this moisture or to prevent this moisture from accumulating in the materials through proper storage and protection from rain and flooding during construction. If such measures are included in the design and construction plans, the initial conditions to be used are the equilibrium moisture content (EMC) of each material at 80% relative humidity (RH). The prescribed design initial moisture content of concrete is EMC at 90% RH if specific care is taken to limit initial moisture conditions. If no such measures are planned, the design moisture contents are doubled.

Indoor Environment

Interior conditions include temperature and humidity. The choice of these conditions is extremely important, especially for design analysis of buildings in cold climates. The indoor conditions in buildings and in different zones within buildings can vary considerably; for example, a warehouse will have much different conditions from a swimming pool or shower room. ASHRAE Standard 160 encourages designers to use their own design parameter values if the values are known and part of the design, or if values are prescribed by code, regulation or law, to

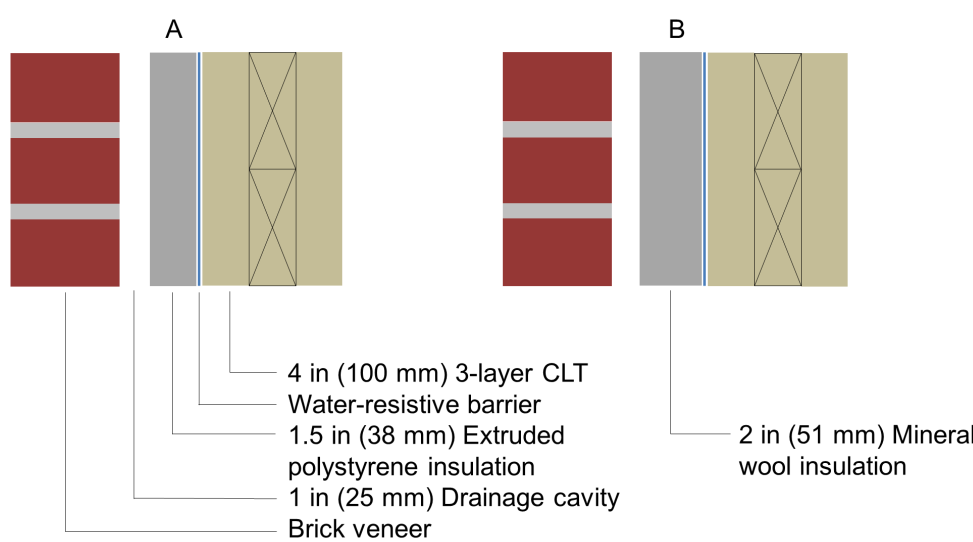

Figure 2. Example Cross-Laminated Timber (CLT) Wall Assemblies.

use those values. If indoor conditions are unknown or not included in the design, the standard provides a simplified procedure or default values. In residential buildings, indoor humidity is rarely explicitly controlled, and default design assumptions are usually needed for these buildings. The standard includes three different methods for determining indoor humidity conditions: simplified method, intermediate method, and full parametric calculation. The reliability of the intermediate method was recently improved with Addendum b to the standard, which is based on analysis of measured indoor humidity and ventilation data. In addition to ASHRAE Standard 160, several European and International standards provide methods for determining indoor conditions (e.g., ISO 2001, DIN 2007). Judgment is needed to select conditions appropriate for the particular building use or occupancy and the particular climate.

Outdoor Environment

Exterior conditions include loads from wind, rain, temperature, humidity, and solar radiation. Severity of conditions can vary considerably from year to year. ASHRAE Standard 160 requires the use of 10 consecutive years of weather data or the use of "Moisture Design Reference Years" (MDRY) to ensure that the analysis is done with appropriately severe weather conditions. In the current standard MDRYs are defined as the 10th-percentile warmest and 10th-percentile coldest years from a 30-year weather analysis (based on mean annual temperature). The standard includes simple formulas for design rain loads on walls for those users who are not inclined, or capable to perform a full wind-driven rain analysis. The standard assumes that some amount of this rain water will penetrate behind the cladding even when adequate flashing is included in the design. The reason is that claddings are usually not completely water tight, especially around windows, doors, and other penetrations. In the absence of specific full-scale test methods and data, the default penetration rate is 1% of the rain deposited on the cladding. The default deposition site for this water is the exterior side of the water-resistive barrier (WRB). If no WRB is present, the designer needs to specify where the water is deposited.

Performance Criteria

Performance criteria are needed to evaluate the results from the design analysis. A detailed overview of failure criteria for building materials is given by Viitanen and Salonvaara (2001). Potential concerns relevant to wood-based structural systems are wood decay, mold growth, corrosion of metal fasteners (see the article by Zelinka in this issue of Wood Design Focus), expansion/contraction damage, and loss of structural capacity. ASHRAE Standard 160 focuses on surface mold growth criteria because under most circumstances these criteria are likely to be the most stringent of all performance criteria (wood decay and structural damage require higher moisture levels and longer duration than mold growth). The standard (as updated in Addendum a) specifies that surface relative humidity on a 30-day running average basis shall be less than 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F). This criterion is thought to be overly simplistic and too restrictive for many cases, and the Standard 160 committee is considering replacing this criterion with a detailed transient mold growth model.

Comparative Hygrothermal Analysis

An alternative to use of performance criteria is to draw comparisons between different variations on a given assembly. Rather than using pass/fail criteria, this approach looks at relative performance between assemblies based on certain metrics. There can be many uncertainties in model inputs, particularly in material properties and boundary conditions, as discussed above. This means that there is generally a higher level of confidence that the simulations will accurately predict relative performance of different assemblies than that the simulations will accurately predict the absolute performance of any given assembly. However, the clear disadvantage is that even the better performing assemblies may still be unsuitable for the climate and interior conditions, and a judgment is still needed. But this can be addressed by including a design that is known to perform well under those conditions. Comparative analysis could involve evaluating assemblies that differ in terms of type of insulation, placement of insulation, or type of vapor retarder, for instance. Analysis could also assess the sensitivity of assemblies to variation in material property values, variation in boundary conditions such as indoor humidity or wind-driven rain, and inclusion of moisture transfer mechanisms such as air leakage. Further examples of this approach can be found in Straube and Smegal (2009), Finch et al. (2013), and Glass (2013).

Simulation Examples

To show the usefulness of hygrothermal analysis in the design of wood buildings, we provide two brief examples and in each case compare the performance of different wall assemblies.

Wood-Frame Construction

This example looks at the drying performance and seasonal trends for oriented strand board (OSB) sheathing in each of the wood-frame wall assemblies shown in Figure 1. The effects of wind-driven rain intrusion and air leakage are not included, both of which significantly change the results. Simulations are started on October 1 at a moisture content of roughly 25% and run for a three-year period. The walls are oriented north and use a climate file from Baltimore, Maryland. Note that the water-resistive barrier is highly vapor permeable.

Figure 3 shows the simulated OSB moisture content for all four walls. The simulations illustrate the effects of an interior vapor retarder and different types of exterior insulation. The baseline wall (A) has a kraft vapor retarder and no exterior insulation. The OSB dries readily and has a repeating annual cycle of lower moisture content in summer and slightly higher moisture content in winter. Wall B omits the kraft vapor retarder (interior latex paint functions as a Class III vapor retarder). This wall dries at approximately the same rate initially, but then accumulates moisture during winter because water vapor migrates more readily through the wall cavity into the OSB from the interior. Wall C adds extruded polystyrene (XPS) insulation between the siding and WRB. Here the OSB dries more slowly because XPS has a low vapor permeance. However, the peak OSB moisture content in subsequent winters is lower than in Wall B because the XPS keeps the OSB warmer (and therefore less prone to moisture accumulation). Wall D changes the XPS exterior insulation to rigid mineral wool exterior insulation. In this wall the OSB dries much faster because mineral wool is highly vapor permeable. During winter the OSB moisture content in Wall D is less than in Wall C because the permeable mineral wool allows water vapor to pass through the OSB to the exterior at a higher rate than XPS.

In summary, this example shows the importance of including an interior vapor retarder (kraft paper) when exterior insulation is not present (assuming no air leakage), and shows that highly permeable exterior insulation allows faster drying than exterior insulation with low vapor permeance. Further details of the simulations, particularly the model inputs with reference to ASHRAE Standard 160 and simulated response of various wall assemblies to wind-driven rain intrusion and to air leakage, can be found in Glass (2013).

Cross-Laminated Timber (CLT) Construction

This example looks at the seasonal performance of the CLT wall assemblies shown in Figure 2, with particular focus on the potential for solar-driven inward diffusion from brick veneer, which is a moisture reservoir cladding. The simulations use a climate file from Houston, Texas. Walls are oriented southeast, which is the predominant direction for wind-driven rain for this weather file. Although rain absorption by the brick veneer is included, intrusion of rain past the cladding is not. The drainage cavity is modeled with an air exchange rate of 2 air changes per hour. Air leakage through the assembly is not modeled. Simulations are started on October 1 at a moisture content in equilibrium with 80% RH and run for a three-year period.

Figure 4 shows the simulated wood moisture content for two CLT wall assemblies. The wood MC for the outermost ½ in (13 mm) of CLT is selected because this location is most sensitive to high exterior humidity conditions. The wall with XPS exterior insulation shows almost no seasonal trend and a very slight drying over three years. The wall with exterior mineral wool insulation accumulates moisture during summer and fall and dries during winter and spring. The climate file happens to have most of the rain occurring in summer and fall. During these seasons, rain wets the brick veneer and moisture migrates inward through the vapor permeable mineral wool insulation into the CLT. Further information regarding the effects of cladding, type of exterior insulation, and climate for CLT wall assemblies can be found in Chapter 10 of the U.S. CLT Handbook (Glass et al. 2013).

Concluding Remarks

This article emphasizes the importance of considering moisture performance during the design process and presents a brief introduction to computer-based hygrothermal simulation as a tool for building envelope design analysis. As with any simulations, the results are only as good as the provided inputs; hygrothermal simulations are sensitive to indoor and outdoor conditions as well as material properties. ASHRAE Standard 160, *Criteria for Moisture-Control Design Analysis in Buildings*, addresses the need for standardized moisture design loads and performance criteria. Comparative hygrothermal analysis can be useful for predicting the relative performance of different building assemblies or investigating sensitivity to certain model inputs. Simulations of light-frame and cross-laminated timber wall assemblies included here illustrate the usefulness of hygrothermal analysis in the design of wood buildings.

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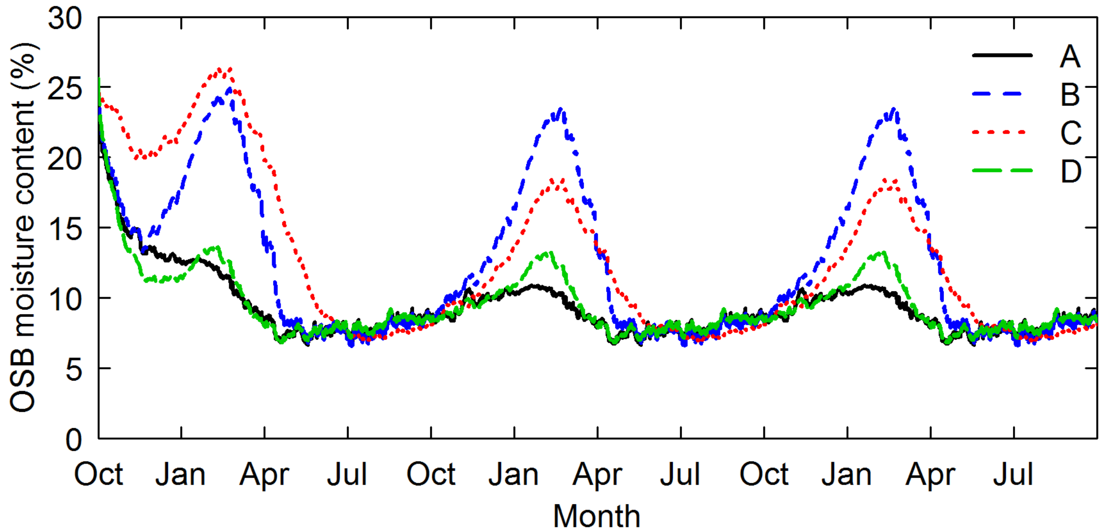

Figure 3. Simulated Moisture Content in OSB Sheathing over Three Years for Wall Assemblies A (Kraft Vapor Retarder, No Exterior Insulation), B (No Kraft, No Exterior Insulation), C (No Kraft, Extruded Polystyrene Exterior Insulation), and D (No Kraft, Mineral Wool Exterior Insulation) (see Figure 1). The Walls are North-Facing and Located in Baltimore, Maryland.

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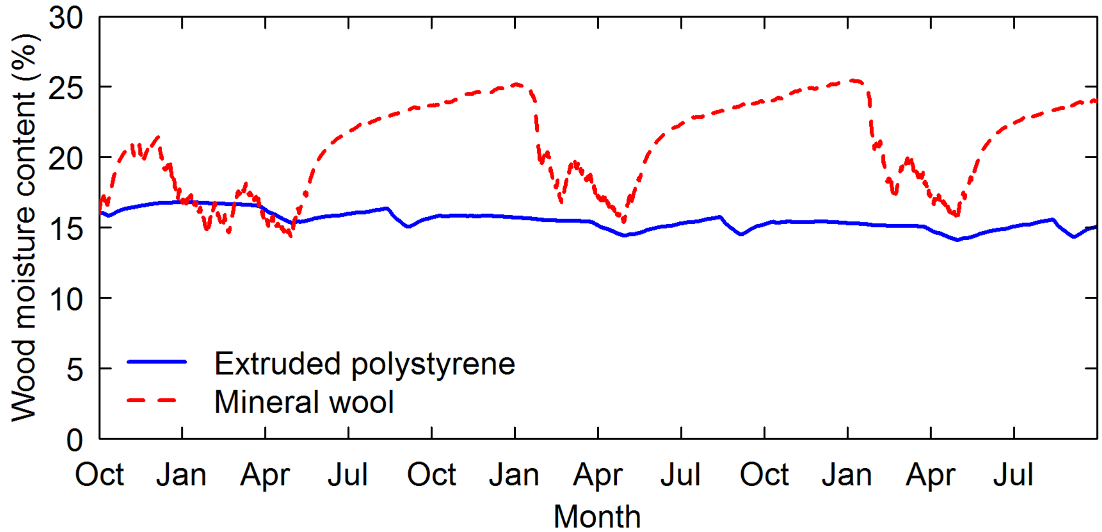

Figure 4. Simulated Moisture Content in the Outermost ½ in (13 mm) of CLT over Three Years for Wall Assemblies with Either Extruded Polystyrene or Mineral Wool Exterior Insulation (see Figure 2). The Walls are Southeast-Facing and Located in Houston, Texas.

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Fastener Corrosion: A Result of Moisture Problems in the Building Envelope

Samuel L. Zelinka, Ph.D.

Abstract

This paper reviews recent literature on the corrosion of metals embedded in wood and highlights the link between moisture accumulation in wood and fastener corrosion. Mechanisms of fastener corrosion are described including dependence upon wood moisture content. These fundamental concepts are applied to practical examples by explaining how hygrothermal models can be used to predict fastener corrosion in wood and showing how fastener corrosion affects the strength of wood-metal connections. The goal of the paper is to familiarize professionals in the wood design community with corrosion.

Introduction to Corrosion of Embedded Metals

Metal fasteners embedded in wood are subject to corrosion from organic acids present in the wood. When present, fire-retardant or preservative treatments may increase the corrosiveness. Over the last 10 years, there has been an increased interest in fastener corrosion because of a shift in commercially available wood preservatives. In January 2004, chromated copper arsenate (CCA) was voluntarily withdrawn from service for residential applications and newer wood preservatives such as alkaline copper quaternary (ACQ) and copper azole (CA) were introduced. Several years later, so called "micronized" formulations were introduced to the market. In these formulations, soluble copper is not injected into the wood; rather solid copper, copper oxide, or copper carbonate is ground into submicron particles ("micronized") and suspended in solution prior to injection. Not surprisingly, the newer wood preservatives have varying degrees of corrosivity, and the lack of previous data onthe wood preservatives has caused some confusion and concern regarding the durability of metal fasteners embedded in wood.

The wood preservatives mentioned above use copper as a biocide, and for these treatments the corrosion mechanism of embedded fasteners involves the reduction of cupric ions introduced by the wood preservatives. The role of cupric ions in the corrosion mechanism was first hypothesized by Baker (1988) and later confirmed by work of Zelinka (Zelinka et al. 2010; Zelinka and Stone 2011) and Kear (Kear et al. 2008; Kear et al. 2009) through energy dispersive x-ray analysis, Pourbaix diagrams, and examinations of the role of cupric ion concentration and acidity. Several studies have also shown that as the copper concentration increases, so does the corrosion rate of embedded fasteners (Kear et al. 2009; Zelinka and Rammer 2011). Table 1 summarizes the composition and required retention for several wood preservatives and highlights the differences in copper concentration. CCA has the lowest copper concentration of the preservatives listed in Table 1 and is also the least corrosive.

An important difference between the corrosion of fasteners embedded in wood and atmospheric corrosion involves passivation. Passivation refers to the process through which corroding metals form a protective oxide or hydroxide layer (patina). In atmospheric corrosion, the corrosion kinetics of steel and zinc are affected by passivation and the corrosion rate decreases with time (Legault and Preban 1975; Legault and Pearson 1978). However, for metals embedded in wood, the corrosion rate has been found in multiple studies to be constant with time (Baker 1992; Zelinka and Rammer 2009). Another difference between atmospheric corrosion and embedded metals involves the relative corrosion rates of different metals. In atmospheric corrosion, zinc forms a passivating zinc carbonate layer that greatly reduces the corrosion rate; however, Zelinka et al. (2010) have examined the corrosion products of steel and zinc fasten-

Table 1: Summary of Some Waterborne Wood Preservatives and Above Ground Retentions Highlighting the Difference in Copper Concentration Between Preservatives. Data are Combined from ((Anon 2007; Lebow 2010)).

Preservative	Composition	Above ground retention (kg of preservative per m^3 of wood)	Copper Concentration (g of copper per m^3 of wood)
CCA	47.5% chromium trioxide 34.0% arsenic pentoxide 18.5% copper as copper oxide	4	591
ACQ	67% copper as copper oxide 33%DDAC	4	2141
CA-B	96.1% amine copper as Cu 3.9% Tebuconazole	1.7	1634
CA-C	96.1% amine copper as Cu 1.95% Tebuconazole 1.95% Propiconazole	1.0	961
ESR-1721 (MCA-B)	96.1% amine copper as Cu 3.9% Tebuconazole	1.0	961
ESR-1721 (MCA-C)	96.1% amine copper as Cu 1.95% Tebuconazole 1.95% Propiconazole	0.8	769
ESR-1980	67% copper as copper oxide 33%DDAC	2.4	1285
ESR-2240	96.1% copper particles 3.9% Tebuconazole	1.0	961

ers and found that embedded fasteners do not form zinc carbonate. This difference in corrosion products is consistent with observations that zinc galvanized fasteners corrode more rapidly than steel fasteners when embedded in wood (Zelinka 2007; Zelinka et al. 2008; Zelinka and Rammer 2009; Zelinka et al. 2010).

Role of wood moisture content in corrosion

How fast metals corrode in wood depends upon the wood moisture content. There is a threshold moisture content between 15-18% MC below which embedded metals do not corrode (Baker 1988; Dennis et al. 1995; Short and Dennis 1997). Above this threshold, the corrosion rate increases rapidly with MC, and possibly plateaus above fiber saturation (Dennis et al. 1995; Short and Dennis 1997).

Despite the importance of moisture, there has been little work examining the effect of moisture content on the corrosion of embedded metals because of experimental limitations. Gravimetric tests are limited because they take six months to a year to complete and the wood moisture content needs to remain constant for the entire test. Previous gravimetric measurements have included at most 3 different moisture conditions, all of which were in the hygroscopic moisture content range (which could be achieved by adjusting the relative humidity) (Baechler 1939, 1949; Kear et al. 2009). The most thorough examination of the moisture content used electrochemical tests where a piece of metal was sandwiched between two pieces of wood (Dennis et al. 1995; Short and Dennis 1997). The data of Dennis et al. (1995) are shown in Figure 1 which plots the corrosion current density (proportional to corrosion rate) as a function of wood moisture content.

Zelinka et al. (2011) fit the electrochemical data in Figure 1 to a simple model and scaled it so that the maximum corresponded with corrosion rates measured for hot-dip galvanized steel in ACQ-treated wood (Figure 2). Figure 2 can be used to estimate the corrosion rate as a function of the wood moisture content for hot-dip galvanized steel in ACQ-treated wood. Since the corrosion rate does not change with exposure time, this equation can be used to estimate the instantaneous corrosion rate when the moisture content of the wood is fluctuating. Therefore, it can easily be combined with a hygrothermal (heat and moisture) model that predicts the wood moisture content from temperature and relative humidity data to assess the risk of corrosion in different building assemblies.

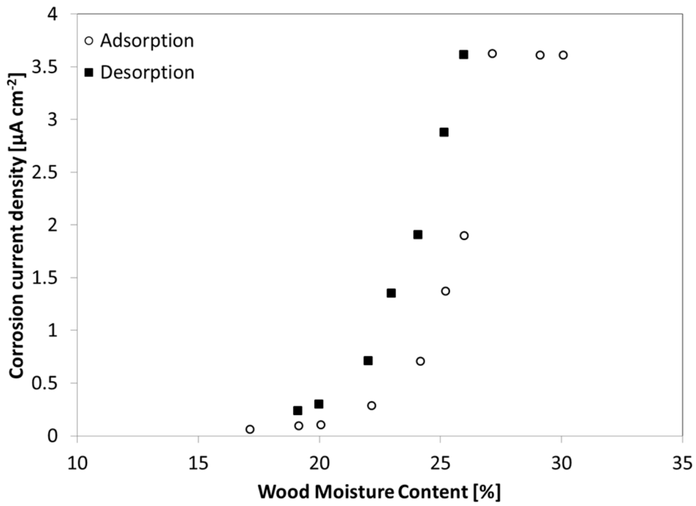

Figure 1: Corrosion Current Density of Galvanized Steel Sandwiched between CCA Treated Wood as Measured by Dennis et al. (1995).

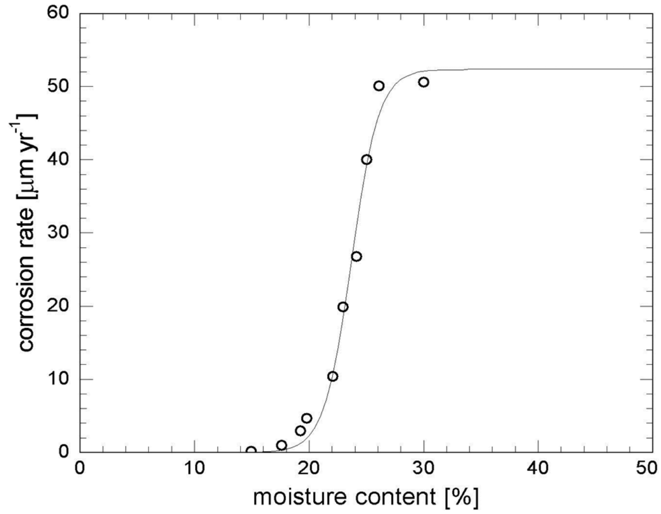

Figure 2: Dependence of the Corrosion Rate Upon the Wood Moisture Content Derived from the Data in Figure 1 and Corrosion Rates Measured by Zelinka et al. (2008) for Galvanized Steel in ACQ-Treated Wood.

Using Hygrothermal Models to Predict Corrosion

Recently, Zelinka et al. (2011) developed a post-processor that can be added to a hygrothermal model to predict corrosion of embedded metals. The corrosion post-processor was developed from the data in Figure 2 and relied upon the assumption that corrosion rate of embedded metals is constant with time as previous data suggest (Baker 1992; Zelinka and Rammer 2009). The two-dimensional finite element model took climatic data as inputs, calculated the wood temperature and moisture content hourly along the entire length of the fastener, and then calculated the instantaneous corrosion rate at each node from the wood moisture content. The instantaneous corrosion rate, which varied along the depth of the fastener, was multiplied by the time increment (an hour) to get the amount of corrosion that occurred during that time step. These hourly corrosion increments were then summed over the entire simulation to give the total depth of corrosion attack along the length of the fastener.

An example of the results of a combined hygrothermal-corrosion simulation is shown in Figure 3 and came from a 2D simulation of a hot-dip galvanized decking nail in ACQ-treated wood. The top surface of the wood was exposed to the full climatic conditions (including precipitation) and the sides and bottoms were exposed to changes in temperature and relative humidity only. The maximum amount of corrosion in the simulations occurred in the first centimeter below the surface of the fastener as this region of the wood remains the wettest for the longest period of time.

The combined hygrothermal-corrosion model is a tool that can be used to design more durable buildings and structures. Currently, the corrosion data are limited to hot-dip galvanized steel in ACQ-treated wood, although current research is underway to make the corrosion postprocessor more adaptable to various treatments and metal types. While the example simulation (Figure 3) showed how corrosion occurred in an outdoor structure, the combined hygrothermal-corrosion model can also be used to model building assemblies and find potential problem spots within the building envelope.

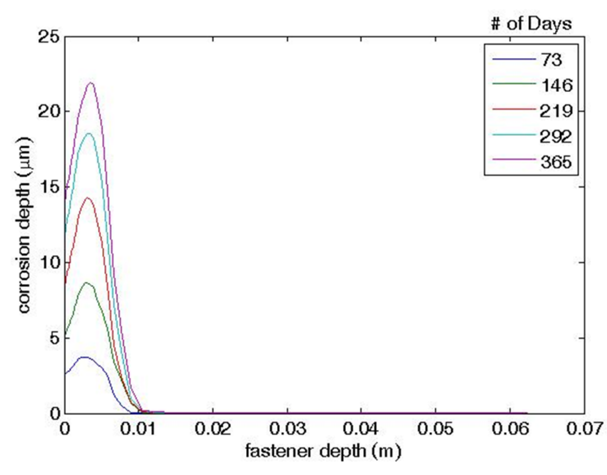

Figure 3: Example Result of a Combined Hygrothermal Corrosion Model Showing the Depth of Corrosion Attack as a Function of the Fastener Depth. The Simulation of a Decking Nail Embedded in ACQ-Treated Wood and Exposed Outdoors Used Climatic Data Collected in Baltimore From 1989.

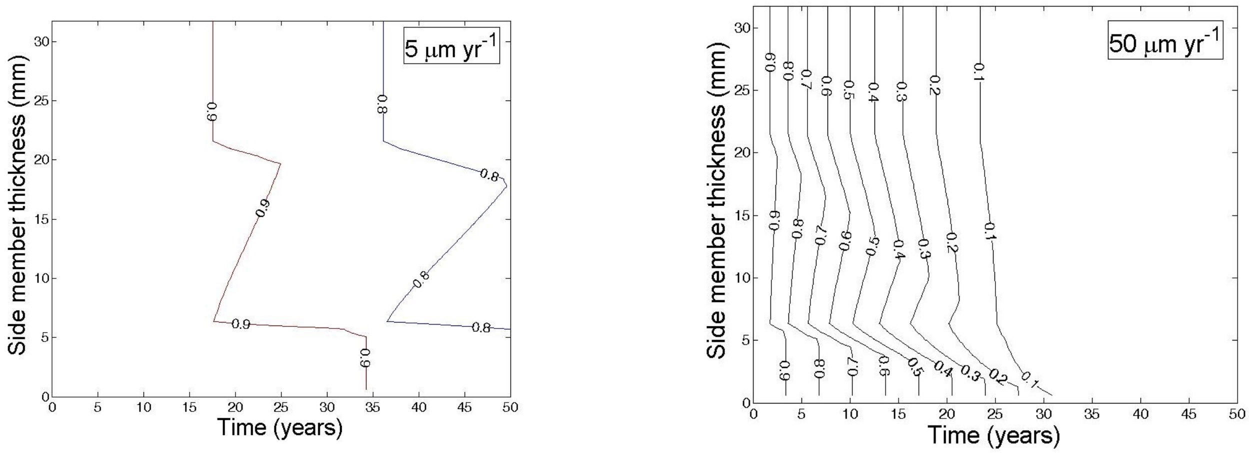

Figure 4: Reduction in Lateral Joint Strength (Contours) for an 8d Nail as a Function of the Joint Geometry and Exposure for Two Different Corrosion Rates. Each Contour Represents a 10% Reduction in Capacity.

Reduction in Mechanical Strength Caused by Corrosion

Most of the research on the corrosion of metals embedded in wood has focused on determining the corrosion rate; however, the magnitude of the corrosion rate is in some ways less important than how the corrosion affects the mechanical property of the joint. Zelinka and Rammer (2012) have used yield theory to examine how corrosion reduces the lateral strength of connections. The fastener connection performance can be calculated by the yield theory developed by Johansen (1949) which treats both the wood and metal as elastic/perfectly plastic materials. The lateral design load, Z (in N), is determined by

$$Z = \min \begin{cases} \dfrac{D T_s F_{es}}{2.2} & (\text{Mode } \mathrm{I_s}) \\ \dfrac{k_2 D l_p F_{em}}{2.2(1+2R_e)} & (\text{Mode } \mathrm{III_m}) \\ \dfrac{k_3 D T_s F_{em}}{2.2(2+R_e)} & (\text{Mode } \mathrm{III_s}) \\ \dfrac{D^2}{2.2}\sqrt{\dfrac{2F_{em}F_{yb}}{3(1+R_e)}} & (\text{Mode IV}) \end{cases} \tag{1}$$

where

$$k_2 = -1 + \sqrt{2(1+R_e) + \frac{2F_{yb}(1+2R_e)D^2}{3F_{em}l_p^2}}$$
$$k_3 = -1 + \sqrt{\frac{2(1+R_e)}{R_e} + \frac{2F_{yb}(2+R_e)D^2}{3F_{em}T_s^2}}$$
and
$$R_e = F_{em}/F_{es} \tag{2}$$

where D is the dowel diameter (mm) $F_{e\_}$ is the dowel bearing stress of the main ($_m$) or side ($_s$) member (MPa), F_{yb} is the bending yield stress of the nail (MPa), l_p is the length of penetration in to main member, and t_s is the thickness of the side member. Since corrosion does not affect the joint geometry, wood dowel bearing stress, or the bending yield stress of the uncorroded fastener, the design load becomes a function of fastener diameter only. If it is assumed that the corrosion products are not structural, then the effect of corrosion can be treated as a reduction in fastener diameter calculated from the corrosion rate.

Figure 4 is a graph of the lateral strength of a connection with an 8d nail (3.4 mm diameter) as a function of joint geometry and time for two different corrosion rates. Each contour in Figure 4 represents a 10% reduction in capacity. The kinks in the contours represent the geometry at which the failure mode changes. From Eq. (1) it can be seen that the Mode IV failure represents a worst case scenario. Figure 5 shows the reduction in capacity as a function of time for many different corrosion rates based upon a Mode IV failure. It can be seen that reduction in capacity of fasteners drops extremely quickly over the range of measured corrosion rates in wood (2-113 micron per year).

Summary

This paper presented a brief overview of the corrosion of metals embedded in wood. Importantly, the corrosion of embedded metals has a different mechanism than atmospheric corrosion. The difference in mechanism explains the relative corrosion rates of steel and galvanized steel observed in wood and also the observation that the corrosion kinetics remain constant with time. The corrosion rate depends strongly on the wood moisture content.

Below 15-18% MC, metals do not corrode; however, once this threshold is crossed, the corrosion rate rapidly increases. This is important as the residual capacity of the joint decreases rapidly with increasing corrosion rate. Finally, a combined hygrothermal and corrosion model was illustrated that predicts the amount of corrosion that will occur in building assemblies. This tool may also be used to determine whether the conditions may warrant selecting a more expensive (corrosion resistant) fastener.

In addition, the following best practices can be used to minimize corrosion of metals in contact with treated wood:

- Keep the wood moisture content below 18%.
- Do not combine dissimilar metals (for example, using a galvanized fastener with a stainless steel joist hanger). This will result in accelerated corrosion.
- When using metals that are protected by paints or other non-metallic coatings, do not damage the coating during installation.

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