Thermal Impact of Fasteners in High-Performance Wood-Framed Walls

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ABSTRACT

Nationwide, energy consumption has lately been the subject of increased research focus, largely because of concerns about climate change and increased international turmoil. Buildings are heavy consumers of energy, and residential building design is rapidly addressing topics to maximize energy conservation.

Annual energy analysis of a building informs the choice among disparate energy measures, for considerations including cost, durability, occupant comfort, and whole-house energy use. Physics-based and empirical models of elements of a building are used in such analyses. High-performance wood-framed walls enable builders to construct homes that use much less than 40% of the energy consumed by similar homes built to minimum code. Modeling for these walls has considered physical features such as framing factor, insulation and framing properties, roughness and convective effects, and air leakage. The thermal effects of fasteners used to construct these walls have not been fully evaluated, even though their thermal conductivity is orders of magnitudes higher than that of other building materials.

Fasteners, namely drywall screws and siding nails, are considered in this finite-element thermal conductivity analysis of wall sections that represent wood-framed walls with 6% to 30% framing factor that are often used in high-performance homes. Nails and screws reduce even the best walls' insulating performance by approximately 3%, and become increasingly significant as the framing factor increases. A correlation coefficient is provided for adjusting high-performance wall R-value.

INTRODUCTION

High-efficiency buildings are gaining significant attention in national policy, and funding for research on high-performance homes has increased substantially (Building America [no date]). One early focus area for energy savings was on improving walls, roofs, floors, and foundations. These elements, which are commonly designed to work together as a functional system, are termed the *enclosure* as they encompass the living space.

Residential buildings have demonstrated substantial energy efficiency improvement by transitioning away from 2 × 4 wall framing on 16 in. (406 mm) centers with glass fiber batt insulation, and toward envelope improvements such as structural insulated panels and advanced insulations. Of particular interest are construction methodologies that meet performance goals without increasing the overall cost to homeowners. Walls constructed using "advanced framing" meet this need, and regularly reduce construction costs (BSC 2004). Advanced framing in this context is defined as 2 × 6 framing on 24 in. (610 mm) centers (NREL 2004). Thermal advantages of advanced framing include the following:

- Wooden framing members have higher thermal conductivity than insulation materials. By using 5.5 in. (140 mm) deep studs (2 × 6) instead of 3.5 in. (90 mm) deep studs (2 × 4), less heat escapes through each framing member.
- Framing installed on 24 in. (610 mm) centers rather than 16 in. (406 mm) centers results in fewer thermal bridges.

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Table 1. Building Materials for Thermal Simulation Model Wall

Layer	Material	Thickness, in. (mm)	Density, lb/in.^{3} (kg/m^3)	Thermal Conductivity, 10^{-6} Btu/s·in.·°F (W/m·K)	Specific Heat, Btu/lb·°F (J/kg·K)	Comment
Drywall	Gypsum	0.50 (12.7)	0.0226 (625)	2.14 (0.16)	0.208 (870)	
Cavity insulation	Blown-in cellulose	5.5 (139.7)	0.00108 (30.0)	0.478 (0.03575)	0.449 (1880)	High-density "R-22"
framing	pine	5.5 (139.7)	0.0166 (460)	1.24 (0.0926)	0.449 (1880)	2 × 6 stud
Sheathing	Rigid foam	1.5 (38.1)	5.20×10^{-4} (14.4)	0.485 (0.03625)	0.351 (1470)	R-4/in. (RSI-27.6/m)
Sheathing	Rigid foam	1.5 (38.1)	5.20×10^{-4} (14.4)	0.276 (0.0206)	0.351 (1470)	R-7/in. (RSI-48.5/m)
Siding	Cement board	0.3125 (7.938)	0.0498 (1380)	3.28 (0.245)	0.201 (840)	Lap siding
Screws	Galvanized steel		0.284 (7870)	575 (43)	0.110 (460)	See text for thermal model dimensions
Nails	Galvanized steel		0.284 (7870)	575 (43)	0.110 (460)	See text for thermal model dimensions
Air	Air		3.97×10^{-5} (1.1)	0.361 (0.027)	0.239 (1000)	

- Increased wall area is devoted to cavity insulation, which is also 57% thicker due to the increased stud depth.

Walls that incorporate advanced framing can be further improved with a continuous layer of exterior rigid insulation. By insulating the exterior of all framing, thermal bridging through remaining wood members, including floor intersections, corners, and around windows, is substantially reduced.

Typical construction methods involve using metal fasteners to assemble wooden studs, and to attach other wall members such as drywall and siding. Because fasteners have a small cross-sectional area in relation to the overall wall area, they are typically neglected in thermal modeling of walls. The simplest, and thus most commonly used, method of estimating overall wall heat flux is the ASHRAE parallel-path method (ASHRAE 2009). Fasteners can no longer be neglected because they result in a significant degradation of overall wall thermal performance when continuous exterior insulation is used on high-performance walls, such as those used on most Building America homes. Nails used to support the siding pass through the exterior foam insulation and into the stud, thus bypassing the thermal break and creating an efficient thermal short. Methods to eliminate this thermal short have been investigated previously (Kosny and Christian 1998; Kosny et al. 2007), but have not become common practice among production homebuilders. This work complements studies such as Kosny et al. (1998), which investigated complicated thermal bridging effects.

Representative high-performance walls have been simulated under thermal loading conditions to explore the overall wall effect of these thermal shorts and to estimate degradation factors for use in numerical simulation.

THERMAL MODEL

The wall construction chosen for simulation is composed of typical building materials. Table 1 shows material details used for thermal simulation. The cutaway image in Figure 1 depicts a full wall and model section.

SolidWorks 2008, SP5.1, was used on a Windows® XP 64 bit computer with 24 GB of RAM and a 3.0 GHz quad-core processor to perform three-dimensional finite-element analysis (FEA). CosmosWorks 2008, SP5.1, was then used to conduct thermal finite-element simulations. Boundary conditions were applied as shown in Figure 2. This wall section was chosen for its lines of symmetry. All edge faces without explicit boundary conditions applied are considered insulated. A temperature of 100°F (37.8°C) was applied to all exposed exterior faces of the siding, and a temperature of 70°F (21.1°C) was applied on the interior face of the drywall. As shown in Table 1, all material properties are taken from Kumaran (2002), except properties of air, for which the CosmosWorks material library values were used. Kumaran provided values at different temperatures and moisture content, but these were not monotonic, so a single value was used. The air gap between siding and foam sheathing is quite thin, so heat transfer contribution from convection was assumed to be negligible. For each wall studied, I calculated steady-state

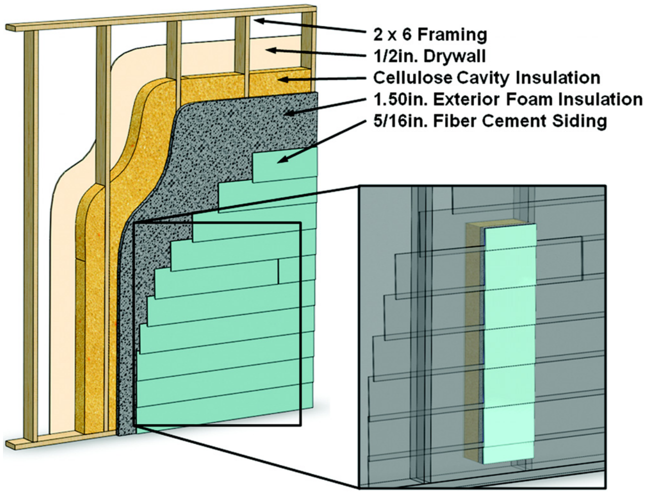


Figure 1 *Cutaway depiction of a high-performance wall. Inset shows the thermal model section for finite-element modeling.*

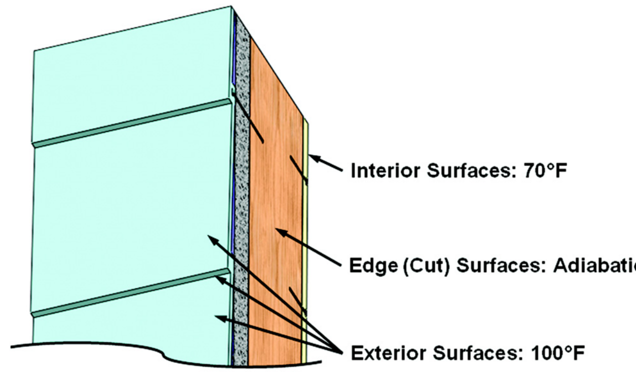


Figure 2 *Boundary conditions used for finite-element simulation.*

overall wall thermal resistivity, which is independent of the temperatures used. Thus, the results of this analysis do not depend on the choice of these temperatures and the $\Delta T = 30°F$ (16.7°C) was for convenience.

Framing factor is a commonly used term designating the area percentage of the overall wall which is occupied by framing members. In residential construction, framing factors between 11% and 25% are common (Kosny et al 2006). Five framing factors were modeled, from 6% to 30% in 6% increments, to enable the thermal bridging impact to be estimated. Dimensions and details for the models are provided in Table 2. Framing factor was simulated using a lumped component whereby the sample's framing was modeled as a single vertical stud of full height and width as given in Table 2. These model geometries were partially driven by the process of estimating fastener densities, and partly by siding manufacturer installation instructions. The lap siding was modeled as 9 in. (229 mm) wide pieces, with an overlap of approximately 1 in. (25 mm) to make the siding periodic on an 8 in. (203 mm) vertical spacing. Models were simulated with R-4/in. (RSI-28/m) exterior foam sheathing and high-density blown cellulose cavity insulation.

Each siding nail was modeled with the head fully embedded and flush with the siding surface, and centered on the overlap. The drywall nails were modeled with the head surface parallel to the drywall interior, fully embedded by 0.05 in. (1.3 mm) to approximate the drywall joint compound. The fasteners were modeled as rectangular extrusions rather than cylindrical to simplify the meshing process. Cross-sectional area was kept constant. Fastener heads were 0.30 in. × 0.30 in. (7.6 mm × 7.6 mm) and 0.10 in. (2.5 mm) thick. The fastener shafts were 0.11 in. × 0.11 in (2.8 mm × 2.8 mm). Siding nails were 2 in. (79.4 mm) long, and drywall screws are 1.625 in. (41.3 mm) long. Screw threads and siding nail ribs were not modeled.

Estimating Fastener Quantities

Fastener densities were estimated as follows. Drywall screws are installed approximately 16 in. (406 mm) apart vertically, or four fasteners per sheet per stud. Further, it was estimated that the drywall screws around corners, partial sheets, doors, and windows amounted to five fasteners per full sheet of drywall. That estimate results in Equation 1, which was used to calculate fastener quantities for the finite-element wall samples in order that these models represent the average thermal performance for the nonfenestration portion of the walls. A similar method was used to estimate siding nail quantities, resulting in Equation 2. Equations 3 and 4 are formulated for SI units.

$$N_{Screws} = (0.0429 \times \%FF + 0.156) \times A_{Wall} \quad (1)$$

$$N_{Nails} = 1.5 \times H_{Wall} + 0.017 \times A_{Wall} \times \%FF \quad (2)$$

or

$$N_{Screws} = (0.4613 \times \%FF + 1.682) \times A_{Wall,\,SI} \quad (3)$$

$$N_{Nails} = 4.92 \times H_{Wall,\,SI} + 0.185 \times A_{Wall,\,SI} \times \%FF \quad (4)$$

where

%FF = wall framing factor, %
A_{Wall} = plan area of wall sample, ft^2
$A_{Wall,SI}$ = plan area of wall sample, m^2
H_{Wall} = wall sample height, ft
$H_{Wall,SI}$ = wall sample height, m

These equations were used to select the smallest finite-element model with a representative quantity of fasteners. The resultant model details are given in Table 2. Drywall screws could be simulated in 1/4 screw increments by placing a screw

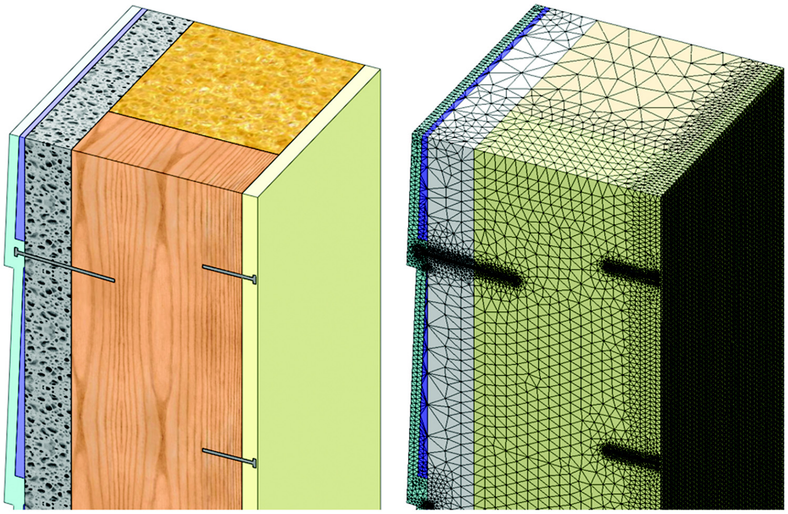


Figure 3 *Example of mesh used for 30% framing factor model with nails and screws.*

Table 2. Finite-Element Wall Sample Details

Framing Factor, %	Qty. of Siding Courses	Wall Sample Height, in. (mm)	Wall Sample Width, in. (mm)	Stud Width, in. (mm)	Eq. 1 Qty. Drywall Screws	Simulated Qty. Drywall Screws	Eq. 2 Qty. Siding Nails	Simulated Qty. Siding Nails
6	6	48 (1219)	12 (305)	0.72 (18)	1.65	1.75	3.41	3.5
12	5	40 (1016)	10.5 (267)	1.26 (32)	1.96	2	3.10	3
18	6	48 (1219)	10 (254)	1.80 (46)	3.09	3	4.03	4
24	5	40 (1016)	9 (229)	2.16 (55)	2.96	3	3.53	3.5
30	5	40 (1016)	8 (203)	2.40 (61)	3.20	3.25	3.64	3.5

at the model's corner, whereas the finest increment of siding nails is 1/2 (by centering the nail on the model's symmetric edge).

Mesh Details

The standard mesh algorithm was used on the high-quality setting, with automatic transition between parts. Fasteners were meshed using 0.055 in. (1.4 mm) elements, the stud meshed with 0.30 in. (7.6 mm) elements, and drywall and siding were meshed with 0.15 in. (3.81 mm) elements. The remainder was meshed with 0.7 in. (17.8 mm) elements. Numerous simulations were conducted to explore results sensitivity to the mesh size, and these settings provided results consistent with much finer meshes. An image of one model and its resultant mesh is provided in Figure 3.

RESULTS

Thermal conductivity of each finite-element model was determined and an R-value was calculated. These results were then contrasted with both a rule-of-thumb estimate and a calculation using the ASHRAE parallel-path method (ASHRAE 2009). The rule of thumb is intended to represent the estimate a typical home builder might give, and is actually the nominal insulating value along a path through the wall cavity. The ASHRAE parallel-path method is a calculation used to estimate overall wall performance, including a simplified thermal bridging effect for the wall's framing.

Typical NZEH High-Performance Wall

A series of wall models was simulated to represent a common high-performance wall construction at different framing factors. These walls have 1.5 in. (39 mm) of R-4/in. (RSI-28/m) exterior sheathing. Figure 4 shows the temperature profile and transverse (inward) heat flux in one wall model. Results are given in Figure 5.

The simulation steps were as follows:

1. Each wall was modeled without fasteners. These models are called "FEA, Blank Wall" in Figure 5. Compared to the parallel-path method calculations, these simulations showed that walls have reduced R-values because of the three-dimensional heat conduction paths not accounted for by the parallel-path method.

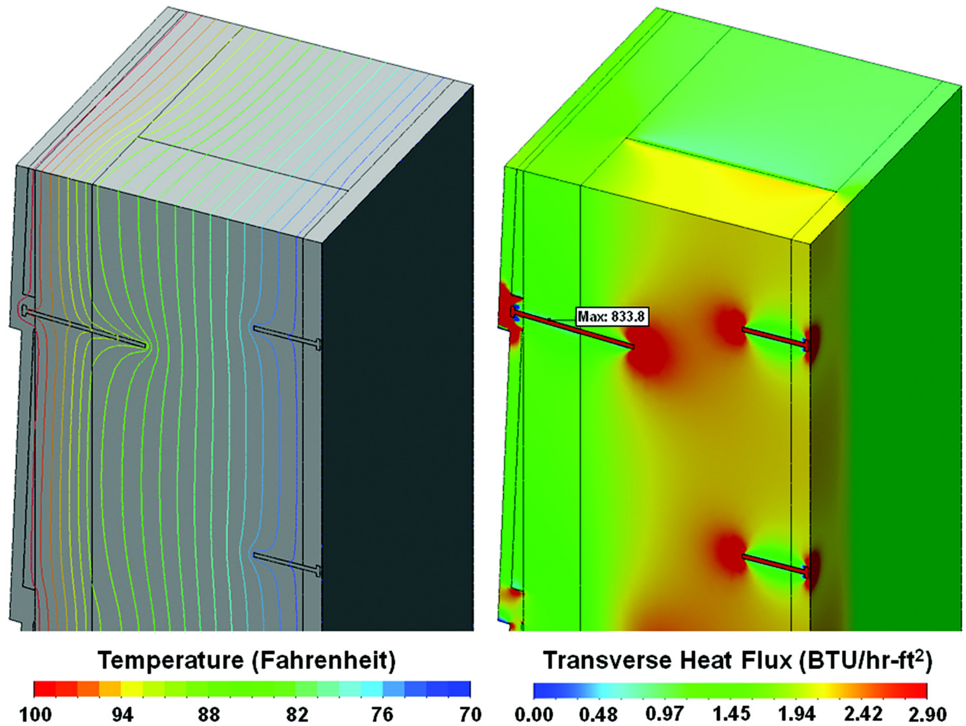
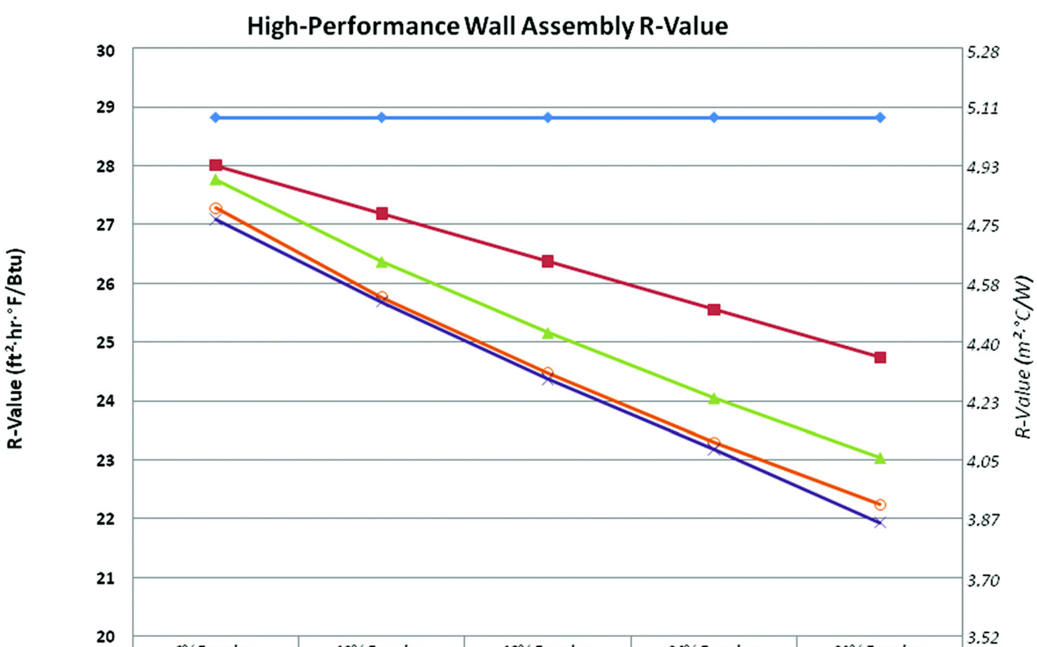
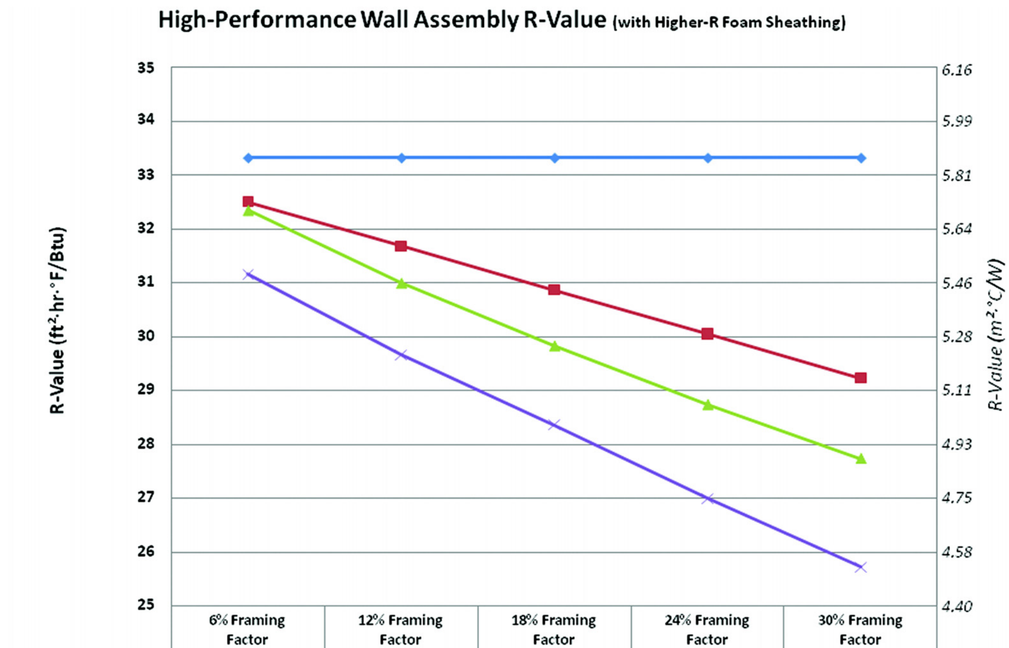


Figure 4 *Results from simulation of a 30% framing factor high-performance wall with fasteners. Image on right shows the transverse component of heat flux only.*



	6% Framing Factor	12% Framing Factor	18% Framing Factor	24% Framing Factor	30% Framing Factor
Rule of Thumb	**R-28.82** *RSI-5.076*	**R-28.82** *RSI-5.076*	**R-28.82** *RSI-5.076*	**R-28.82** *RSI-5.076*	**R-28.82** *RSI-5.076*
Parallel Path	**R-28.01** *RSI-4.932*	**R-27.19** *RSI-4.788*	**R-26.37** *RSI-4.644*	**R-25.55** *RSI-4.500*	**R-24.74** *RSI-4.356*
FEA, Blank Wall	**R-27.77** *RSI-4.891*	**R-26.37** *RSI-4.643*	**R-25.16** *RSI-4.430*	**R-24.05** *RSI-4.235*	**R-23.04** *RSI-4.058*
FEA, Siding Nails	**R-27.28** *RSI-4.804*	**R-25.77** *RSI-4.538*	**R-24.47** *RSI-4.309*	**R-23.29** *RSI-4.101*	**R-22.24** *RSI-3.916*
FEA, Nails + Screws	**R-27.09** *RSI-4.770*	**R-25.72** *RSI-4.523*	**R-24.37** *RSI-4.291*	**R-23.18** *RSI-4.082*	**R-21.93** *RSI-3.863*

Figure 5 *Results from calculation and simulation of high-performance walls with R-4/in. (RSI-28/m) sheathing insulation.*



	6% Framing Factor		12% Framing Factor		18% Framing Factor		24% Framing Factor		30% Framing Factor	
Rule of Thumb	R-33.32	RSI-5.869	R-33.32	RSI-5.869	R-33.32	RSI-5.869	R-33.32	RSI-5.869	R-33.32	RSI-5.869
Parallel Path	R-32.51	RSI-5.725	R-31.69	RSI-5.581	R-30.87	RSI-5.437	R-30.05	RSI-5.293	R-29.24	RSI-5.149
FEA, Blank Wall	R-32.35	RSI-5.698	R-31.00	RSI-5.459	R-29.83	RSI-5.254	R-28.74	RSI-5.062	R-27.74	RSI-4.885
FEA, Nails+Screws	R-31.16	RSI-5.488	R-29.67	RSI-5.225	R-28.36	RSI-4.995	R-27.00	RSI-4.755	R-25.73	RSI-4.531

Figure 6 *Results from calculating and simulating high-performance walls with R-7/in. (RSI-48.5/m) exterior insulation.*

2. These walls were modeled with siding nails included. Siding nails were expected to affect overall wall R-value more than drywall screws because they thermally bridge the sheathing insulation. These simulations show that the expected thermal shorts do occur, resulting in an R-value decrease of R-0.5–R-0.8 (RSI-0.087–RSI-0.142) compared with the blank wall.
3. Each wall was modeled with siding nails and drywall screws. The combined effect of drywall screws and siding nails results in an additional small decrease in R-value, in the range of R-0.1–R-0.3 (RSI-0.034–RSI-0.053).

The simulated effect of fasteners is a 2.5%–4.8% decrease in overall wall R-value. Interestingly, the impact of three-dimensional effects (0.8-6.8%) can be greater than that of fasteners. Compared with parallel-path calculations, the simulated walls with all fasteners show an overall 3.3%–11.3% decrease in R-value. The decrease in R-value is larger as framing factor increases.

High-Performance Wall with Improved Insulation

Exterior sheathing at R-7/in. (RSI-48.5/m) rather than R-4/in. (RSI-27.6/m) was then used to simulate a similar series of wall models. The intermediate walls with siding nails but no drywall screws (Step 2 above) were not simulated. Results from these simulations, seen in Figure 6, were similar to above. Overall R-value decrease of the walls with fasteners, compared with parallel-path calculation, is 4.1–12.0%. This demonstrates that modeling the fasteners becomes more important as the framing factor increases and insulation performance increases.

Estimate of R-Value Decrease

A simple formula that can effectively estimate the decrease in R-value resulting from the three-dimensional effects, including fasteners, in this common type of wall construction is desirable. Sixteen additional simulations were completed to explore the effect of insulation thickness. Both 3 in. (76 mm) and 1 in. (25 mm) thick insulations were simulated, to complement the 1.5 in. (38 mm) thickness used above. In each case, the length of the siding nails was adjusted to obtain the same insertion into the stud as the prior models, which were based on siding manufacturers' installation instructions.

A thermal degradation coefficient was calculated for each wall. The coefficient is defined as

$$C_{TD} \equiv \frac{R_{simulated}}{R_{ParallelPath}} \tag{5}$$

Linear regression was then used to determine an effective correlation between insulation properties and degradation coefficient. Surprisingly, a very simple correlation was extremely accurate.

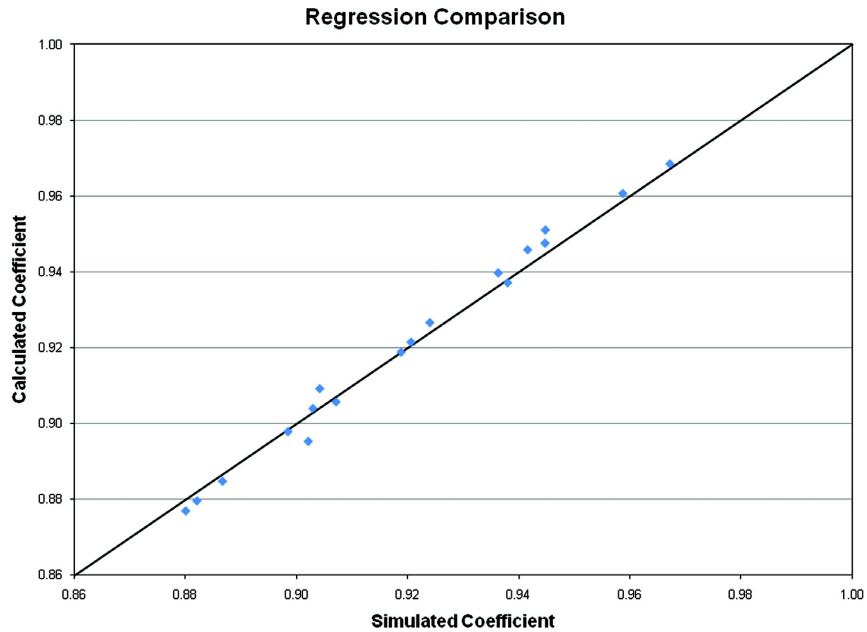


Figure 7 *Comparison of degradation coefficients determined by calculation to simulated values.*

$$C_D = 1 - 0.003494 \times \%FF - 0.001742 \times R_{insul} \tag{6}$$

or

$$C_D = 1 - 0.003494 \times \%FF - 0.009891 \times RSI_{insul} \tag{7}$$

where

%FF = framing factor, %

R_{insul} = R-value of sheathing insulation, $ft^2 \cdot h \cdot °F/Btu$

RSI_{insul} = R-value of sheathing insulation, $(m^2 \cdot °C)/W$

This equation fit the simulated data with $R^2 = 0.9985$, and the numerical fit varied only slightly when regression was performed on significantly smaller selections of the data. Comparison of coefficients determined by calculation versus the simulated values is given in Figure 7.

CONCLUSIONS

In this work, a series of walls were simulated using three-dimensional finite element methods. A steady-state thermal analysis was used to calculate R-value for each wall section. The walls were chosen to be approximately representative of the high-performance wood-framed walls that are becoming common in energy efficient home construction throughout the United States.

The results demonstrate that three-dimensional effects and fasteners have a large thermal impact on the overall wall R-value. These effects are not considered with simple estimation methods such as the ASHRAE parallel-path method. Overall wall R-value was shown to decrease by 3.3–12.0%.

An adjustment factor was found to closely match the simulation results. The overall wall R-value, calculated using the ASHRAE parallel-path method, may be multiplied by this factor to obtain an improved estimate of the real-world R-value for walls analyzed above. This equation is valid only for walls of the type simulated in this work, but the method probably could be used to similar effect in different wall constructions. This equation should only be used for framing factors between 6% and 30%, sheathing insulation conductivities between R-4/in. (RSI-27.6/m) and R-7/in. (RSI-48.5/m), and sheathing insulation thicknesses between 1 in. (25 mm) and 3 in. (76 mm). Further, the engineer should use judgment about whether the fastener densities given by Equations 1 and 2 are appropriate for the application.

FUTURE WORK

Several limitations of this study may be addressed in future work. First, the effect of the model assumptions should be considered. Boundary conditions can be improved. The interior and exterior faces of the wall are not maintained at a constant temperature, as demonstrated in Figure 8 by infrared thermography, which shows the effects modeled in this study. The wall areas at and near the studs of a real wall are clearly visible, and dark spots are seen where fasteners are located. This study neglected external convective and radiative heat transfer, phenomena that must be included to accurately model whole-building energy consumption. This work is expected to support advanced combined heat transfer modeling.

Material property variance with temperature and moisture content could be used to extend this work. Variation of

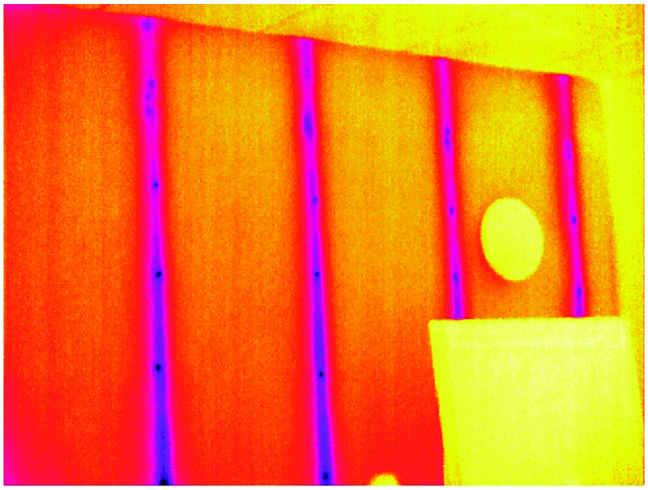


Figure 8 *Infrared thermograph of an interior wall, showing the thermal bridging impact of fasteners and studs.*

Photo credit: Dane Christensen/NREL PIX #17526.

thermal conductivity with temperature is simplest to include, and is a common feature of finite element modeling software. Moisture can result in substantial differences in material properties, but its effect on overall wall heat transfer is much more difficult to simulate.

The air spaces between the siding and foam are expected to convect. This may substantially alter the heat transfer in that area. Radiative heat transfer is unlikely to be significant in this air space because the sheathing foam is typically coated in a reflective foam foil. Infiltration and exfiltration could also be considered, but are not expected to be significant because high-performance walls of the type simulated in this work are usually sealed very tightly.

Finally, the estimates of fastener density may be inconsistent with some builders' practices. There are wide variations in wall assembly practices and fastener requirements. Lateral fasteners, such as those used in framing out the horizontal studs around a window, were excluded from this work because they are expected to make a substantially lesser contribution to thermal degradation. They are oriented perpendicular to the main heat flux, so will play a less significant role.

Other topics for future work include modeling other types of walls, such as staggered-stud and 2 × 4 constructions. Also, comparing these results to laboratory hot-box measurements on similar wall sections would be interesting.

REFERENCES

ASHRAE. 2009. *2009 Handbook–Fundamentals*, Ch. 25: Heat, air, and moisture control in building assemblies—Fundamentals, p. 25.7. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

BSC. 2004. *BSC final report: Lessons learned from Building America participation, February 1995–December 2002*. Report SR-550-35915. Golden, CO: National Renewable Energy Laboratory, Building Science Corporation.

Building America. (no date). *Building America*. Washington, DC: US Department of Energy. http://www.building america.gov/.

Kosny, J. and J. Christian. *Whole wall thermal performance*. Oak Ridge, TN: Oak Ridge National Laboratory. http://www.ornl.gov/sci/roofs+walls/research/detailed_papers/Whole_Wall_Therm/index.html.

Kosny, J., J. Christian, A. Desjarlais, E. Kossecka, and L. Berrenberg. 1998. Performance check between whole building thermal performance criteria and exterior wall measured clear wall R-value, thermal bridging, and airtightness. *ASHRAE Transactions* 104(2).

Kosny, J., D. Yarbrough, P. Childs, and S.A. Mohiuddin. 2006. Effects of framing on the thermal performance of wood and steel-framed walls. *Proceedings of the Fifteenth Symposium on Improving Building Systems in Hot and Humid Climates*, Orlando.

Kosny, J., T. Petrie, D. Yarbrough, P. Childs, A. Syed, and C. Blair. 2007. Nano-scale insulation at work: Thermal performance of thermally bridged wood and steel structures insulated with local aerogel insulation. *Thermal Performance of the Exterior Envelopes of Buildings X, Proceedings of ASHRAE THERM X*, Clearwater, FL.

Kumaran, M., J. Lackey, N. Normandin, F. Tariku, and D. van Reenen. 2002. *RP-1018—A thermal and moisture transport property database for common building and insulating materials*. Report D-8222. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

NREL. 2004. *Whole-house approach benefits builders, buyers and the environment.* Report DOE/GO-102004-2014. Golden, CO: National Renewable Energy Laboratory. http://apps1.eere.energy.gov/buildings/publications/ pdfs/building_america/34867.pdf.