Evaluating the Thermal Performance of Mass Walls Compared to Wood-Framed and Steel-Framed Walls in Residential Buildings using *EnergyPlus*

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Abstract

While homes across the United States are traditionally built using wood-frame construction, mass or concrete walls are popular in certain regions of the country. Mass walls have certain advantages in terms of energy efficiency compared to the lighter wood-frame or steel-frame walls; however, conducting hotbox tests and specialized thermal modelling analyses of these walls to evaluate energy performance is often time-consuming and cost-prohibitive. More importantly, heat transfer in real buildings is a dynamic process consisting of the effects of outdoor air temperature and solar gains in conjunction with infiltration and internal gains. These are not captured through isolated hotbox tests or wall section modelling techniques. The latest state-of-art building energy simulation tools can be utilized to overcome these constraints. This paper describes a comprehensive analysis of different wall types using *EnergyPlus* in all climate zones in the continental United States. The methodology for modelling various wood, steel and mass walls and the development of material properties for use in simulation is described. An overview of the large-scale simulation structure used in the analysis is provided. Resulting energy consumption for various mass walls is included along with a comparison of select mass walls and wood-frame or steel-frame walls. It is observed that mass walls are generally more energy-efficient than wood-framed walls in warm and moderate climate zones and insulation placement is an important consideration in the efficiency of mass walls.

Introduction

The buildings sector is one of the largest consumers of energy in the United States. In 2015, approximately 40% of the total energy consumed in the country was consumed by residential and commercial buildings, totalling approximately 39 quadrillion British thermal units (EIA 2016). With the increase in population, the energy consumption of the residential sector has steadily risen over the years and in 2015, residential buildings accounted for approximately 53% of energy consumed by the entire building sector, more than the commercial sector (EIA 2016).

With a rising demand for energy, efficient use of energy in buildings has been gaining prominence in recent years. Research in this field has led to the development of new and improved building techniques, energy-efficient materials and construction practices. At the same time, older and time-tested building techniques like incorporating thermal mass in exterior walls are gaining renewed interest.

There is a long history of isolated experimental analysis and testing of wall assemblies to determine heat transfer through them. However, heat transfer through an assembly under steady-state testing conditions is quite different from the interactive and dynamic thermal effects that occur in real buildings. This is especially true for walls that incorporate thermal mass. Thermal mass or thermal inertia allows the material to absorb and store heat. Materials like concrete absorb more heat that is available for release later when compared to lightweight wood- or steel-framed walls, thereby delaying the impact of changing environmental conditions on the interior space. To better understand the thermal performance of different wall types, they need to be evaluated in a dynamic environment with changing outdoor and interior conditions to match typical occupied buildings. However, evaluation based on testing would be time-consuming and cost-prohibitive. In lieu of detailed experimental testing, whole building energy simulation can prove to be a good surrogate for evaluating the thermal performance of walls because it also allows for the evaluation of a large combination of walls efficiently and effectively.

The present analysis is conducted using *EnergyPlus*[TM], the latest state-of-art whole building energy simulation program developed by the US Department of Energy (DOE). Based on fundamental principles of heat balance, *EnergyPlus* conducts an integrated and simultaneous simulation of thermal zone conditions and Heating, Ventilation and Air-Conditioning (HVAC) system response at hourly and sub-hourly time steps (EnergyPlus 2016a). It allows the user to specify detailed building geometry, construction materials and HVAC system components using a module-based structure. Weather data for use in simulation is available for over 2100 locations around the world (EnergyPlus 2016b). Automatically varied time steps for interactions between thermal zones and HVAC systems allow the program to model systems with fast dynamics while trading off simulation speed for precision.

The present study is targeted at modelling the interactive energy impacts of a residential building, outdoor environmental conditions, and typical internal load conditions. The house configuration, size, orientation, and load schedules are held constant so that the impact of different wall assemblies in various climate zones can be compared.

Analysis Methodology

This section provides an overview of scope of the present analysis, the available options for modelling walls in *EnergyPlus* and the methodology used by the authors to model various mass, wood-framed and steel-framed walls.

Scope of the Analysis

The analysis covers five main wall types—standard concrete masonry unit (ASTM C90) walls (CMUs), reduced-web concrete masonry unit (ASTM C90-11b) walls (CMUr), insulated concrete form walls (ICF), wood-framed walls, and steel-framed walls. Each wall type is analysed for multiple selected combinations of insulation levels and placements, for a total of 628 wall combinations.

Each wall combination is incorporated into a whole building simulation using a pair of national one and two-storey single-family prototype building models based on DOE's methodology for calculating energy savings from building energy code provisions during the code development process (Taylor et al. 2015). These prototypes allow for a national perspective of different mass walls. Table 1 summarizes the primary characteristics of each building prototype used in this analysis. Additional details about the models are documented in Hart et al. (2014 and 2016). The models are simulated in all 15 climate zones occurring in the US, as classified by the 2012 edition of the International Energy Conservation Code (ICC 2012). Representative cities used in simulation are summarized in Table 2.

Modelling Heat Transfer through Opaque Building Components in *EnergyPlus*

There are two native methods available for simulation of wall heat transfer in *EnergyPlus*: a conduction transfer function and a finite difference solution algorithm. *EnergyPlus* uses a conduction transfer function (CTF) module to solve transient surface heat flux. The simplest time series solution is a response factor equation, which relates the flux on one surface of an element to an infinite series of temperature histories on both sides. The thermal capacitance of the material layers is accounted for in the calculation for each node at the material interface. This allows the impact of the thermal mass heat storage to be captured in simulation, including the impacts of layer by layer storage and disipation of heat energy. *EnergyPlus* uses the state space method for CTF calculations which allows short time steps and provides solution stability. Studies conducted to compare the simulation results from the *EnergyPlus* CTF method with an improved CTF method and a finite volume method concluded that the prediction from *EnergyPlus* compares well with other numerical methods, as well as measured data for inner cavity brick-plaster construction (EnergyPlus 2013). *EnergyPlus* is also one of the few whole-building energy performance simulation programs that support a one-dimensional solution algorithm if the material temperatures within the opaque layers are of interest, for example, analysis of phase change materials or combined heat and moisture transfer. However, this algorithm significantly increases the computation time compared to the basic CTF module, so it was not used.

After reviewing the relative benefits and computing resources for the two wall heat transfer options in *EnergyPlus*, the basic CTF method was selected for this analysis. The CTF method accurately accounts for both heat transfer and thermal storage in walls. The effect of thermal bridging in *EnergyPlus* can be reasonably captured by layers of materials with effective thermal resistances calculated using the isothermal planes or modified thermal zone methods.

Table 1: Primary Characteristics of Building Prototypes Used in the Study

Basis	DOE Prototypes for IECC Analysis with parameters from 2012 IECC	
Storeys	1	2
Conditioned Area (ft^2)	2000	2200
Foundation	Slab on Grade	Vented Crawl Space
Building Shape	Rectangular	
Window Area	15% of conditioned floor area, equally distributed to the four cardinal directions	
Heating Type	Natural Gas Furnace; Electric Heat Pump; and Electric Resistance Furnace	
Cooling Type	Split system with DX cooling coil	
Water Heating	Natural Gas Storage Tank (40 gal)	

Specifying Opaque Building Components in *EnergyPlus*

There are two different strategies for specifying walls in *EnergyPlus*, both suitable for building energy efficiency analyses. While both approaches are able to utilize a layer-by-layer specification of the component assembly, the first approach requires only the thermal resistance of each layer (in ft^2-F-hr/Btu or m^2-K/W). This approach uses the *EnergyPlus* "Material:NoMass" object to specify

the required layers and is suitable for component assemblies where the impact of thermal mass is negligible or other detailed material properties are unavailable. The second approach requires detailed information about material properties, mainly the thickness (in inches or meters), conductivity (in Btu-in/ft^2-hr-F or W/m-K), density (in lb/ft^3 or kg/m3) and specific heat (in Btu/lb-F or J/kg-K), for each layer in the assembly. This approach uses the *EnergyPlus* "Material" object to specify the required layers and allows the program to capture effects of mass on heat transfer. Because the present analysis involves modelling and evaluating mass walls, the second approach of specifying detailed material properties through the *EnergyPlus* "Material" object is used. This allows the program to account for the thermal mass of the material, heat storage, and transient conduction effects largely ignored by the first approach that assumes steady-state heat conduction (EnergyPlus 2013).

In simulation, *EnergyPlus* treats each layer specified through the Material object to be a homogenous layer with uniform material properties. In typical residential building construction, exterior walls are assemblies containing several layers. While most of the assembly layers such as gypsum board, concrete face-shells etc. are indeed homogenous; the central framing and insulation layer is made of distinct framing and insulation portions as shown in Figure 1. Depending on the type of the wall, the effective conductivity of this layer can be calculated using the isothermal planes method or the modified zone method.
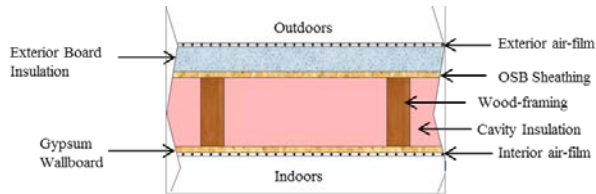

Figure 1: Typical Residential Exterior Wall Assembly

Methodology for Calculating Effective Material Properties for Use in Simulation

As discussed earlier, specifying homogenous layers in *EnergyPlus* is straightforward. However, the central insulation layer requires special consideration because it is a combination of two or more materials with very different conductivities. The framing portion of the layer, typically made from wood, steel or concrete is a better conductor of heat, and thus has a higher conductivity, than the insulation portion. This results in two distinct heat transfer paths through the wall, each characterised by a different conductivity. When heat flows through the wall, it takes the path of least resistance (or higher conductivity). The heat transfer through the central insulation layer can be modelled numerically like the current flow through resistances placed in series and parallel as shown in Figure 2.
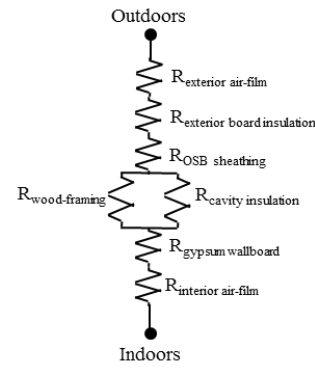

Figure 2: Equivalent Resistances Diagram of the Exterior Wall shown in Figure 1

Thus, the effective conductivity of the framed layer is best calculated so that the resulting heat transfer through the composite homogenous layer would be the same as if the framing and insulation areas were modelled explicitly as separate areas. The appropriate method for calculating the effective conductivity depends on the type of the wall. For example, the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) recommends and the isothermal planes method for wood-framed walls, the modified zone method for steel framed walls. The methodology used for calculating the effective conductivity, density and specific heat of the composite mass/framing and insulation layer for each wall type considered in the present analysis is described in detail below.

Wood-Framed Walls

Wood-framed walls are the most commonly used wall type in residential construction in the United States. For this analysis, the wood-frame wall assembly layers are assumed to be an exterior air film, synthetic stucco, insulating sheathing (if applicable), 7/16" thick oriented strand board, a composite framing and insulation layer, 1/2" thick gypsum board and an interior air film. All layers, except the composite framing and insulation layer can be specified into *EnergyPlus* directly using the material properties from the ASHRAE Handbook of Fundamentals (ASHRAE 2009).

The handbook recommends the isothermal planes method for calculating the effective conductivity of the composite framing and insulation layer for wood-frame walls. Furthermore, the handbook recommends a framing area fraction of 25% for all wood-framed walls (ASHRAE 2009). The effective conductivity can thus be calculated using the area fraction for the framing and cavity portions and the conductivity associated with lumber and fiberglass batt insulation respectively. The equations are dtraightforward and not included here for brevity. Table 3 summarizes the material properties for the composite framing and insulation layer for the various levels of insulation considered in this analysis.

Standard Concrete Masonry Unit (CMUs) Walls

The CMU wall assembly modelled in this analysis consists of an exterior air film, cementitious or synthetic stucco, exterior foam insulation (if applicable), CMU block (with various levels of insulation and grouting), interior foam insulation (if applicable), fiberglass batt insulation within wooden framing members (if applicable), interior airspace with furring, 1/2" thick gypsum board and an interior air film. Depending on the wall configuration of interest, layers are included or excluded from the model specification. Again, all layers, except the CMU block layer can be entered directly into *EnergyPlus* using the material properties specified in the ASHRAE Handbook of Fundamentals (ASHRAE 2009). The CMU block layer requires special consideration.

The ASHRAE handbook indicates that the resistance of masonry walls can be calculated assuming a combination of layers in series, one or more if which provides parallel paths (ASHRAE 2009). Standard concrete masonry units consist of two cells separated by concrete webs as shown in Figure 3. Considering the direction of heat flow through the wall, the unit can be divided into the inner and outer face-shells made of concrete and a central composite web and cell layer. Using the same general approach, the face-shells can be directly specified in *EnergyPlus* as two concrete layers of the required thickness, conductivity, density and specific heat.
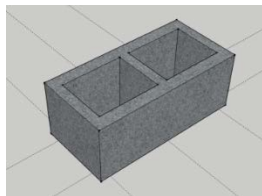

Figure 3: Typical Standard Concrete Masonry Unit

The effective thermal conductivity for the composite web and cell layer of the CMU walls with fully simulation-filled, completely empty and completely grouted cells is calculated using the isothermal planes method recommended by ASHRAE. First, the area fractions for the web, grouting and cavity are calculated based on the dimensions of the CMU block and grout spacing. For a standard CMU block, the area fraction of webs remains constant at 17.87% for all cases. In a fully grouted configuration, all cells are filled with grout leading to an area fraction of 82.13% for grouting and 0% for the cavity. In a configuration with no grouting, the area fraction for grouting becomes 0% and that for the cavity becomes 82.13%. For partially grouted configurations, the area fraction for grouting is calculated using grout spacing. The area fraction for cavity is calculated as 100% minus the area fraction for grouting and webs.

The next step involves calculating the thermal resistance (R-value) for CMUs walls with completely empty cells, fully insulation-filled cells, and fully grouted cells. This is done by applying the isothermal planes method to composite web and cell layer using area fractions and conductivities for concrete webs, grouting and insulation. Dividing the thickness of the composite layer by the effective conductivity yields the R-value for the composite web and cell layer. The R-values of the face shells, mortar layers, and air-films are added to the central composite web and cell layer to calculate the overall R-value for the wall assembly. The R-value is then converted to heat transfer coefficient (U-factor).

The wall assembly U-factor for partially grouted walls is calculated using a combined area weighting and isothermal planes method described in NCMA Tek 6-2C document (NCMA 2013). The U-factors of the completely empty, fully insulation-filled, and fully grouted walls calculated above are area-weighted using area fractions for the partially grouted wall configuration to yield the overall resistance of the complete wall assembly. The R-value of the composite web and cell layer for the partially grouted cases is then back-calculated by removing the R-values of the face shell and mortar layers and air-films. Because *EnergyPlus* requires conductivity and thickness as inputs, the R-values are converted to conductivity based on the thickness of each layer. Composite layer density is calculated by volume-weighting the constituent materials, and specific heat is calculated by mass-weighting the constituent materials. Tables 4 and 5 summarize the calculated material properties for the composite web and cell layer for different configurations of the CMUs walls considered in this analysis. These are used as inputs to *EnergyPlus* for modelling these walls.

Reduced-Web Concrete Masonry Unit (CMUr) Walls

Reduced-web concrete masonry units are similar to the standard-web units except they have two webs per unit instead of three like the CMUs. This design allows the quantity of highly conductive concrete to be reduced and instead be replaced by insulation, resulting in a lower wall U-factor. In typical reduced-web masonry units, the area fraction for webs reduces to 8.94% compared to 17.87% for the standard masonry units, thus allowing 91.06% of the area to be available for insulation or grouting. The procedure for calculating the effective properties of the composite web and cell layer remains the same as the CMUs, barring the different area for webs and the cavity. Tables 6 and 7 summarize the calculated material properties for the composite web and cell layer for different configurations of the CMUr walls considered in this analysis. These are used as inputs to *EnergyPlus* for modelling these walls.

Insulated Concrete Forms (ICF)

Insulated Concrete Forms are modular moulds made with rigid insulation that are interlocked to create the structural framework of a wall. This framework is then filled with concrete to create a permanent wall. Simply put, ICFs are a layer of concrete sandwiched between two layers of rigid insulation. Thus, representing ICFs in *EnergyPlus* requires simply specifying the material properties of the insulation and concrete layers. These properties are readily available in the ASHRAE Handbook of Fundamentals and not repeated here for brevity.

Steel-Framed Walls

Steel-framed walls, although uncommon in residential single-family construction in the United States, are included in this analysis to provide a complete picture. Because steel framing members are highly conductive, the ASHRAE Handbook of Fundamentals recommends a modified zone method for calculating the effective conductivity of the composite framing and insulation layer. This method essentially defines an "affected zone" around the webs of the steel C-studs used in steel-frame construction (ASHRAE 2009). By first calculating the width of the affected zone, the effective thermal conductance is calculated as the sum of contributing areas, similar to an area weighting approach. A brief overview of the steps involved in calculating effective material properties from the energy modelling perspective is included in this section. However, the equations and charts required in calculation are clearly laid out in the ASHRAE handbook of Fundamentatals and are not included in this paper for brevity.

The first step in calculation is the determination of the zone factor (z_f) using the stud spacing, and resistivity of the sheathing, face materials and cavity insulation. The next step is the calculation of the width of the affected zone based on the dimensions of the steel C-stud. Next, the exterior and interior thermal resistances with respect to the position of the C-stud are calculated by adding the resistances of all interior and exterior wall layers. For the wall assembly assumed in this analysis, the interior layers comprise of a single 1/2" thick gypsum board layer while the exterior layers comprise of the applicable exterior insulation, stucco and a 7/16" thick oriented strand board (OSB) layer. The zone width and interior and exterior resistances are substituted in the area weighting equations specified in the handbook to calculate the effective resistances of the sections in the affected zone around the C-stud. These resistances are further weighted to calculate the overall resistance and associated U-factor for the entire wall assembly. The effective resistance of the composite framing and insulation layer is back-calculated by subtracting the R-values of exterior insulation, finishes and air-films. The effective resistance is then converted to conductivity for input into *EnergyPlus* using the thickness of the composite layer.

The area fraction for the metal framing portion is calculated using the dimensions of typical C-studs that correspond to typical 2x4 and 2x6 wood-frame walls (Steel Framing Alliance 2007). This results in a framing area fraction of 0.55% for the equivalent of 2x4 walls that are 3.5" thick and 0.43% for the equivalent of 2x6 walls that are 5.5" thick walls. These area fractions are used in volume weighting the metal and insulation portions to calculate the effective density and the effective specific heat is similarly calculated by mass weighting the metal and insulation portions. Table 8 summarizes the effective properties of the composite framing and insulation layer for various configurations of steel-frame walls used in simulation.

Simulation Process

The analysis is conducted using a specially developed template-parameter simulation platform developed by the authors and other researchers at the Pacific Northwest National Laboratory that allows the creation and simulation of large batches of *EnergyPlus* input files a single step (Mendon and Taylor 2014). The large-scale simulation structure is designed around a central flexible template system configured to edit and assemble snippets of *EnergyPlus* objects into a full simulation IDF, akin to a mail-merge system. This system leverages the text-based format of *EnergyPlus* IDFs for easy manipulation using the Perl programming language (Perl 2016). A separate comma separated (CSV) parameter file specifies the attributes used to build the building energy model. These parameters can range from simple specifications for building geometry or window areas to complex HVAC system attributes. The template system is extremely flexible and completely scalable in terms of handling building geometry, various building component assemblies, HVAC systems as well as internal loads. While most of the template development is done in *EnergyPlus*, the simulation structure is capable of supporting parametric simulations for any program that is based on similar principles.

The procedures for calculating effective material properties for all wall types are implemented in the central template through Perl code. Attributes are then specified in the parameter file to generate building energy models that incorporate all 628 wall assemblies into the two single-family prototype configurations. Each model is simulated in the relevant climate zones using weather data in the Typical Meteorological Year (TMY3) format (EnergyPlus 2016b) to generate hourly and annual energy consumption results. Finally, simulation results are aggregated through automated data mining scripts into summary files. An overview of the large-scale simulation structure using a block diagram is shown in Figure 4.
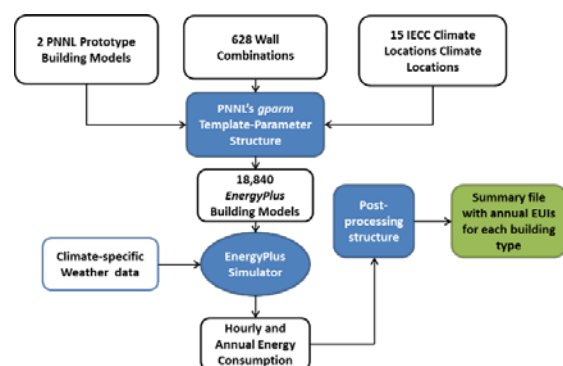

Figure 4: Block Diagram of the Simulation Process

Results

The focus of this study is the development of wall assembly parameters for different types of walls for use with *EnergyPlus*. All wall combinations are incorporated in each of the two single-family prototype models and simulated in multiple climate zones. Thus, the energy

consumption data generated from this analysis is exhaustive and can yield many different types of comparative studies and trend analysis. A few interesting comparisons and results are included in this section for discussion.

Impact of Wall Mass and Insulation Location

A sampling of walls is selected to explore the impact of mass and insulation location on energy consumption of the two-storey single-family prototype with a natural gas furnace. These walls are binned by their unit weight into groups with a range of 5 lbs/ft² of wall area. Figure 5 shows the variation in the HVAC annual energy cost expressed per square foot of conditioned floor area with respect to the wall U-factor for various wood-frame and CMU walls in climate zone 2A, a cooling-dominated hot-moist climate zone represented by Houston, Texas, USA. Figure 6 shows similar data for climate zone 5A, a heating-dominated cool-moist climate zone represented by Chicago, Illinois, USA. The legend indicates the wall weight bin. Energy prices are USA averages for 2014.
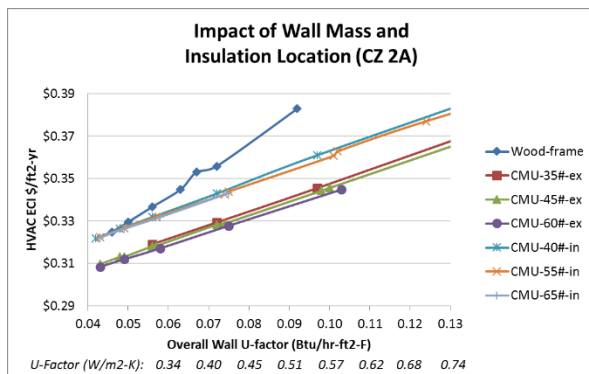

Figure 5: Impact of Wall Mass and Insulation Location for Climate Zone 2A (Houston)
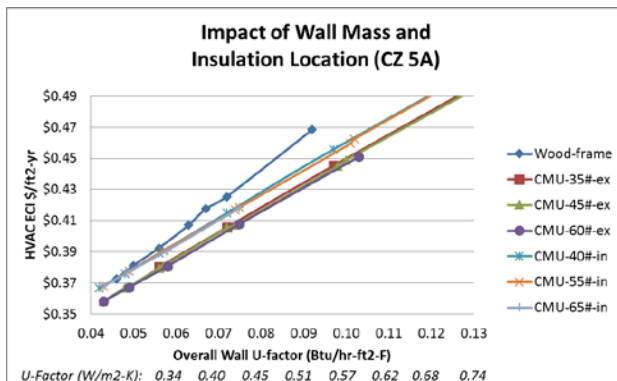

Figure 6: Impact of Wall Mass and Insulation Location for Climate Zone 5A (Chicago)

In the warmer climate zone, the HVAC cost is generally lower for mass walls compared to wood-frame walls for a similar U-factor. This illustrates the benefit of the thermal storage capacity of mass walls and the temperature lag introduced by it for warmer climates. A similar trend is observed in the colder climate zone but the differences are

smaller than those seen in the warmer climate zone. Additionally, the results show that placing the insulation on the exterior of mass walls reduces HVAC cost much more than when the insulation is placed on the interior. The impact of insulation placement is much larger than adding incremental mass to CMU walls.

Energy Consumption of Standard CMU Walls Compared to Reduced-Web Walls

The energy consumption of standard CMUs walls is compared to reduced-web CMUr walls of the same concrete density and insulation level. Figure 7 shows the energy use intensity (EUI) comparison for the two-storey single-family prototype model with a gas furnace. It is observed that the EUI for CMUr walls is lower than that for CMUs walls, so long as the cells are filled with insulation (denoted by "F" in the chart nomenclature). Interestingly, when the cells are empty (denoted by "e" in the chart nomenclature), there is no discernible difference in the energy performance of standard and reduced-web walls. This is due to the conductivity of the 115 lbs/ft³ density webs having a lower estimated conductivity than the empty cells in this case. Similar trends are observed for the prototype model with the electric heat pump.
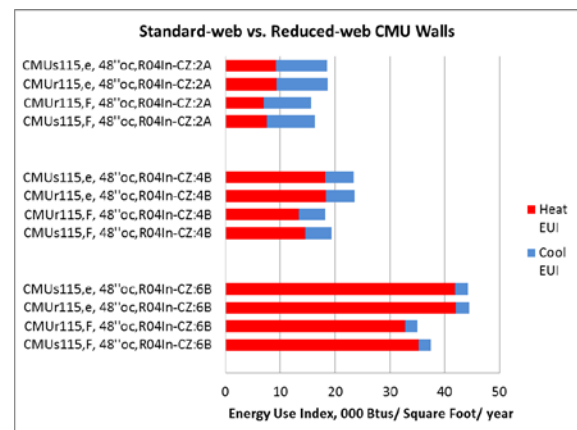

Figure 7: Energy Consumption of Standard CMU Walls Compared to Reduced-Web CMU Walls

Energy Consumption of Typical Wood-Frame Compared to Standard CMU Walls

Because wood-frame construction is widely popular in residential buildings in the United States, energy consumption for a typical wood-frame wall with R-13 cavity insulation is compared with a standard CMU wall with a block density of 115 lbs/ft³ and R-8 interior board insulation in all climate zones. Figure 8 illustrates the heating and cooling EUIs for the two-storey single-family prototype model with a natural gas furnace in all climate zones occurring in the United States. The results show that insulated mass walls result in lower energy consumption in all warm and moderate climate zones. It is only in the extremely cold climate zones, that the wood-frame wall consumes less energy. The differences in energy consumption result from heating energy while cooling energy remains similar between both cases.

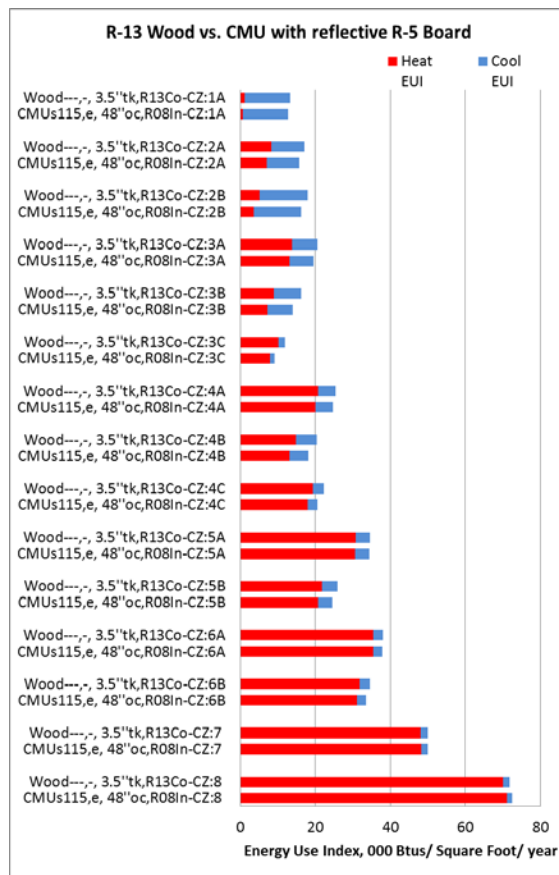Similar trends are observed for the prototype model with the electric heat pump.

Figure 8: Energy Consumption of Typical Wood-Frame Walls Compared to Standard CMU Walls

Conclusion

This paper has shown how whole building energy modelling can be used as an effective surrogate for experimental analysis in evaluating the thermal performance of walls. In addition to being cost-effective and time-efficient, whole building simulation allows for the consideration of the dynamic interaction between indoor loads and the outdoor environment in evaluating wall performance, which is important when evaluating the impact of mass on energy efficiency. The methodology for modelling various types of lightweight and mass walls in *EnergyPlus* is described in detail and the calculated effective material properties for selected combinations of each wall type are included for reference. These can be used to model thermal performance of mass walls in a whole-building environment in any simulation program. Finally, main results from the analysis are discussed. Mass-walls are observed to be more energy-efficient than wood-framed walls in all but the coldest climate zones. Additionally, the placement of insulation is observed to be an important consideration for mass walls with exterior insulation being a more energy efficient configuration than interior insulation. The results from this analysis may be applied to other countries with some caution with respect to the differences in the climate zone classification system.

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Table 2: Representative Cities Used in Simulation

CLIMATE ZONE	CLASSIFICATION	REPRESENTATIVE US CITY
1A	Very Hot, Moist	Miami, Florida
2A	Hot, Moist	Houston, Texas
2B	Hot, Dry	Phoenix, Arizona
3A	Warm, Moist	Memphis, Tennessee
3B	Warm, Dry	El Paso, Texas
3C	Warm, Marine	San Francisco, California
4A	Mixed, Moist	Baltimore, Maryland
4B	Mixed, Dry	Albuquerque, New Mexico
4C	Mixed, Marine	Salem, Oregon
5A	Cool, Moist	Chicago, Illinois
5B	Cool, Dry	Boise, Idaho
6A	Cold, Moist	Burlington, Vermont
6B	Cold, Dry	Helena, Montana
7	Very Cold	Duluth, Minnesota
8	Subarctic	Fairbanks, Alaska

Table 3: Effective Properties of the Composite Framing and Insulation Layer for Wood-frame Walls

WALL COMBINATION	FRACTION FRAMING	FRACTION CAVITY	CONDUCTIVITY (BTU-IN/HR-FT²-F)	THICKNESS (INCHES)	DENSITY (LBM/FT³)	SP. HEAT (BTU/LBM-F)
Wood-frame; R13 cavity	25.00%	75.00%	0.402	3.500	7.563	0.376
Wood-frame; R19 cavity	25.00%	75.00%	0.429	5.500	7.563	0.376

Table 4: Effective Properties of the Composite Web and Cell Layer for Selected Standard CMU (CMUs) Walls with Solid Grouted or Un-Grouted (Completely Empty or Foam-filled) Cells

WALL COMBINATION	FRACTION WEB	FRACTION GROUT	FRACTION CAVITY	CONDUCTIVITY (BTU-IN/HR-FT²-F)	THICKNESS (INCHES)	DENSITY (LBM/FT³)	SP. HEAT (BTU/LBM-F)
CMUs 115 lbs/ft3 concrete density; completely empty cells	17.87%	0.00%	82.13%	5.598	5.125	20.619	0.221
CMUs 115 lbs/ft3 concrete density; completely foam-filled cells	17.87%	0.00%	82.13%	1.211	5.125	22.194	0.230
CMUs 115 lbs/ft3 concrete density; solid grouted cells	17.87%	82.13%	0.00%	9.285	5.125	131.426	0.220

Table 5: Effective Properties of the Composite Web and Cell Layer for Selected Standard CMU (CMUs) Walls with Partially Grouted Cells

WALL COMBINATION	FRACTION GROUTED	FRACTION UN-GROUTED	CONDUCTIVITY (BTU-IN/HR-FT²-F)	THICKNESS (INCHES)	DENSITY (LBM/FT³)	SP. HEAT (BTU/LBM-F)
CMUs 115 lbs/ft3 concrete density; grout spacing 24"; un-grouted cells empty	33.00%	67.00%	6.568	5.125	57.185	0.220
CMUs 115 lbs/ft3 concrete density; grout spacing 48"; un-grouted cells empty	17.00%	83.00%	6.075	5.125	39.456	0.220
CMUs 115 lbs/ft3 concrete density; grout spacing 96"; un-grouted cells empty	8.00%	92.00%	5.817	5.125	29.484	0.220
CMUs 115 lbs/ft3 concrete density; grout spacing 24"; un-grouted cells foam-filled	33.00%	67.00%	2.532	5.125	58.241	0.222
CMUs 115 lbs/ft3 concrete density; grout spacing 48"; un-grouted cells foam-filled	17.00%	83.00%	1.819	5.125	40.764	0.224
CMUs 115 lbs/ft3 concrete density; grout spacing 96"; un-grouted cells foam-filled	8.00%	92.00%	1.481	5.125	30.933	0.226

Table 6: Effective Properties of the Composite Web and Cell Layer for Selected Reduced-Web CMU (CMUr) Walls with Solid Grouted or Un-Grouted (Completely Empty or Foam-filled) Cells

WALL COMBINATION	FRACTION WEB	FRACTION GROUT	FRACTION CAVITY	CONDUCTIVITY (BTU-IN/HR-FT²-F)	THICKNESS (INCHES)	DENSITY (LBM/FT³)	SP. HEAT (BTU/LBM-F)
CMUr 115 lbs/ft3 concrete density; completely empty cells	8.94%	0.00%	91.06%	5.554	5.125	10.350	0.221
CMUr 115 lbs/ft3 concrete density; completely foam-filled cells	8.94%	0.00%	91.06%	0.690	5.125	12.097	0.240
CMUr 115 lbs/ft3 concrete density; solid grouted cells	8.94%	90.40%	0.66%	9.643	5.125	132.316	0.220

Table 7: Effective Properties of the Composite Web and Cell Layer for Selected Reduced-Web CMU (CMUr) Walls with Partially Grouted Cells

WALL COMBINATION	FRACTION GROUTED	FRACTION UN-GROUTED	CONDUCTIVITY (BTU-IN/HR-FT²-F)	THICKNESS (INCHES)	DENSITY (LBM/FT³)	SP. HEAT (BTU/LBM-F)
CMUr 115 lbs/ft3 concrete density; grout spacing 24"; un-grouted cells empty	33.00%	67.00%	6.606	5.125	50.599	0.220

WALL COMBINATION	FRACTION GROUTED	FRACTION UN-GROUTED	CONDUCTIVITY (BTU-IN/HR-FT²-F)	THICKNESS (INCHES)	DENSITY (LBM/FT³)	SP. HEAT (BTU/LBM-F)
CMUr 115 lbs/ft3 concrete density; grout spacing 48"; un-grouted cells empty	17.00%	83.00%	6.069	5.125	31.085	0.220
CMUr 115 lbs/ft3 concrete density; grout spacing 96"; un-grouted cells empty	8.00%	92.00%	5.790	5.125	20.108	0.221
CMUr 115 lbs/ft3 concrete density; grout spacing 24"; un-grouted cells foam-filled	33.00%	67.00%	2.003	5.125	51.769	0.223
CMUr 115 lbs/ft3 concrete density; grout spacing 48"; un-grouted cells foam-filled	17.00%	83.00%	1.287	5.125	32.534	0.226
CMUr 115 lbs/ft3 concrete density; grout spacing 96"; un-grouted cells foam-filled	8.00%	92.00%	0.954	5.125	21.715	0.230

Table 8: Effective Properties of the Composite Framing and Insulation Layer for Selected Steel-Frame Walls

WALL COMBINATION	FRACTION STEEL	FRACTION CAVITY	CONDUCTIVITY (BTU-IN/HR-FT²-F)	THICKNESS (INCHES)	DENSITY (LBM/FT³)	SP. HEAT (BTU/LBM-F)
Steel-Frame; R13 cavity, R0 continuous	0.550%	99.450%	0.604	3.500	3.436	0.137
Steel-Frame; R13 cavity, R4 continuous	0.550%	99.450%	0.507	3.500	3.436	0.137
Steel-Frame; R13 cavity, R8 continuous	0.550%	99.450%	0.522	3.500	3.436	0.137
Steel-Frame; R13 cavity, R10 continuous	0.550%	99.450%	0.541	3.500	3.436	0.137
Steel-Frame; R13 cavity, R15 continuous	0.550%	99.450%	0.611	3.500	3.436	0.137
Steel-Frame; R19 cavity, R0 continuous	0.433%	99.567%	0.794	6.000	2.863	0.141
Steel-Frame; R19 cavity, R4 continuous	0.433%	99.567%	0.705	6.000	2.863	0.141
Steel-Frame; R19 cavity, R8 continuous	0.433%	99.567%	0.740	6.000	2.863	0.141
Steel-Frame; R19 cavity, R10 continuous	0.433%	99.567%	0.776	6.000	2.863	0.141
Steel-Frame; R19 cavity, R15 continuous	0.433%	99.567%	0.890	6.000	2.863	0.141