Impact of Mass Wood Walls on Building Energy Use, Peak Demand, and Thermal Comfort

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ABSTRACT

For nearly a century, thermal energy demand calculations have been based on simplified models limited by the technical potentials of the period. The first action took place in Germany and Austria in 1929, when the initial technical standards committee for heating was founded. The calculation methods initiated then, to a surprisingly significant extent, still apply today. In addition to the climate zones for German and Austrian locations, initial consensus established conductivity coefficients of building materials and heat transfer coefficients. In 1959, heat transfer coefficients and modern building materials were integrated. Ever since, at least for mass timber buildings, the coefficients for conductivity have been subject only to relatively insignificant innovative change. Steady-state hot-box assessment methods have been used to assess mass timber buildings, generally ignoring thermodynamic characteristics, which have demonstrated significant advantages in mass timber buildings in practice. Novel methodologies have been applied in the research performed at a US DOE national laboratory. The inclusion of the thermal comfort approach based on and in accordance with DIN 7730 and ASHRAE Standard 55 has demonstrated significant differences in the energy requirement assessments performed dynamically. The research results bring the assessment data much closer to the anticipated heating demand in practice. Thermal inertia, inner surface temperatures, thermal emissivity, solar gains, dynamic outer weather conditions, and thermal comfort characteristics are finally combined into a holistic assessment. These results can potentially be applied towards the contribution of energy-efficient mass timber buildings; and, moreover, to material-efficient mass timber buildings at the same time, while material efficiency is becoming ever more important.

INTRODUCTION

Homes with solid mass wood walls (MWW) contribute to roughly 1.5% of all new home starts, or 7% of custom home starts in the US. The MWW market in the US has risen from nearly \$65 Million to over \$170 Million in 2019, with projections to almost \$400 Million by 2025. By application, the Cross Laminated Timber (CLT) market is segmented into residential buildings, educational institutes, government and public buildings, and industrial and commercial spaces. Residential buildings held the largest global revenue share in 2020, i.e., around 45% (Grand View Research 2021). The demand for wooden residential buildings, including multifamily apartments and single-family homes, is rising. In addition,

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CLT homes' earthquake resiliency, improved fire resistance qualities, and embodied carbon benefits are anticipated to drive markets further. The global cross-laminated timber market size was estimated at USD 955.9 million in 2020 and is expected to expand at a compound annual growth rate (CAGR) of 13.6% from 2021 to 2028 (Grand View Research 2021).

CLT-based buildings take less time to construct; because mass timber panels are prefabricated, smaller crews can safely assemble more structural elements in less time. The speed advantage is amplified because manufacturing can coincide with site and foundation work, reducing downtime between construction phases and shortening construction time. The building codes are also being updated to include CLT and other innovative engineered wood materials in taller buildings. Several mass timber code change proposals were approved for inclusion in the 2021 International Building Code (IBC 2021). The timber code change proposals create three new types of construction in the United States, setting fire safety requirements and allowable heights, areas, and number of stories for tall mass timber buildings up to 18. However, guidance towards thermal designs which make the best use of the thermal characteristics, e.g., high thermal mass, cooling load reduction potential, contribution to thermal comfort through warmer walls in heating periods, and air temperature reduction potential due to fulfilled thermal comfort criteria, is not available.

The thermal benefits of mass wood structures are not well-known in the industry. It is anticipated that cooling needs can be significantly reduced and postponed into periods beyond the peak demand times. It is also expected that heating loads may be lower than the energy demand calculations predict, which is, however, to be researched in another research project after this one. That can be justified by the ongoing research and assessment in practice regarding the mass timber industry, resulting in thermal comfort effects that seem to make up for differences between calculations and real-time heating energy consumption.

In this project, novel methodologies, compared to classic hot-box assessments, have been applied; however, only to a certain extent due to budget and time. Furthermore, contrary to static conditions, the focus was on switching to dynamic conditions, as experienced in practice. More details of the study can be found in Salonvaara et al., 2022.

Thermodynamic factors are crucial for assessing massive building components, such as CLT elements. Inner and outer (real-world) conditions are not limited to fixed temperatures and controlled airflow. Although the hot-box approach is reliable for steady-state transmission measurements, it does not measure thermal inertia. Thermal inertia plays a significant role in mass wood buildings. Similarly, thermal inertia is a measure of the thermal mass and the rate of temperature change on the surface of a material. In heat transfer, a higher value of the volumetric heat capacity results in a longer period for the material to reach equilibrium. People can lose up to 60 % of thermal energy through radiation, making the surface temperatures of building components crucial for thermal comfort. Furthermore, the studies on thermal comfort demonstrate how important the operative temperature is compared to solely assessing air temperature.

Objectives

The project goal was to obtain data to inform opportunities to further improve the thermal efficiency of buildings' envelopes by measuring the thermal performance of mass-timber (CLT) structures. This study provided input to building heating and cooling energy simulations to show thermal performance benefits (total energy, peak demand) when mass-timber is substituted for standard framed systems. Up to 50% lower cooling energy use during peak cooling hours was estimated due to the thermally optimized CLT structure's time shift of the heating load. These savings can translate to significant cost savings when time-of-use rates are applied, while at the same time, peak loads for cooling can be significantly reduced, which potentially results in grid overload reduction.

VALIDATING SIMULATIONS MODELS WITH LABORATORY TESTS

Thermal performance measurements in Large Scale Climate Simulator

The test chamber used in this study was a national laboratory's Large Scale Climate Simulator (LSCS). The simulator controls the exterior climate in the upper chamber and the indoor climate in the lower chamber.

Four test assemblies were constructed and assembled in the test frame for testing in the LSCS. The walls included two lightweight (2x4 and 2x6) and 4in (102 mm) and 6 ¾in (171 mm) CLT walls (Table 1). The exterior surfaces of the walls were painted white to have the same absorptance for the radiation from the heat lamps. The walls were installed horizontally on the frame that was lifted into the chamber. Each wall section was thermally separated by 2in (51mm) of extruded polystyrene insulation.

Table 1. Wall assemblies in LSCS tests.

Wall	Naming Convention	Description from indoors to outdoors
2x4, 3.5in (89 mm) Lightweight	LW4	½in (12.5 mm) Gypsum board, R13 (RSI-2.3) batts 16in (406 mm) oc*, 7/16in (11.1 mm) OSB
2x6, 5.5in (140 mm) Lightweight	LW6	½in (12.5 mm) Gypsum board, R23 (RSI-4.1) batts 24in (610 mm) oc, 7/16in (11.1 mm) OSB
4in (101 mm) CLT	CLT4	½in Gypsum board (12.5 mm), 4in (101 mm) CLT
6 ¾in (171 mm) CLT	CLT6	½in Gypsum board (12.5 mm), 6 3/4in (171 mm) CLT

* oc = on center distance between studs

Temperature and heat flux measurements

Temperature sensors (Type T thermocouples) were placed on four interfaces on the lightweight walls: 1) on the exterior surface, 2) between OSB and fiberglass insulation, and between OSB and stud, 3) between fiberglass insulation and gypsum board, and between stud and gypsum board, and 4) on the interior surface. Heat flux sensors were placed in location 3.

The CLT walls do not have OSB on the exterior and are homogeneous with solid wood instead of insulation and framing. The heat flux transducers were placed on locations 1 and 2, defined below. The temperature sensors were placed on three interfaces: 1) on the exterior surface, 2) between CLT and gypsum board, and 3) on the interior surface.

Laboratory Tests to Compare Mass Timber and Lightweight Wall Structures

The weather conditions for the laboratory testing were chosen to be those in Golden, CO, which represents IECC climate zone 5B. Golden, CO, has cold winters and sunny days, providing temperature swings on walls between night and day that encompass the interior temperature conditions. Typical daily temperature and solar radiation profiles were taken for February and August using the TMY3 weather files in EnergyPlus.

The hourly surface temperatures on a lightweight wall assembly facing south orientation were calculated using a hygrothermal simulation tool (Fraunhofer Institute for Building Physics). The hourly surface temperatures were then used to control the surface temperature on the light wall assembly in the laboratory tests to mimic the performance when exposed to those weather conditions. Heat lamps were used to control the surface temperature on the lightweight wall representing the impact of solar radiation. The heat lamps provided the same radiation intensity on all four specimens. The air temperature in the climate chamber was set 5ºF lower than the minimum target surface temperature to allow for the surface temperature to reach the low nighttime value.

The climate simulator controls allow for eight periods per day as step changes in temperature. Therefore, the temperature setpoints don't follow the profile at every hour but supply a reasonable simulation of the diurnal cycle. The indoor conditions were set to a constant 69ºF.

Comparison of Measured and Simulated Performance in Laboratory Conditions

The measurements continued for about a week per season, repeating the 24-hour scheduled hourly temperatures in the climate chamber. The winter schedule was run first, followed by a stabilization and summer schedules. The assemblies were simulated with COMSOL Multiphysics (COMSOL) to evaluate the simulation model performance and establish the material parameters of the whole building simulation model EnergyPlus v9.6 (DOE, 2021a). The simulations were carried out sequentially for the winter and summer conditions.

Figure 1 compares the measured and simulated heat fluxes through two wall assemblies, the 2x4 lightweight wall (LW4) and the 6 ¾in CLT wall (CLT6), for the full test period, including the winter and summer test conditions. The simulations match the measured results well, including the time response (thermal mass impact) and the level of heat flux, with simulations predicting slightly lower heat fluxes than measured for the lightweight wall. In addition, the simulations match the measured heat flux in the CLT wall extremely well.

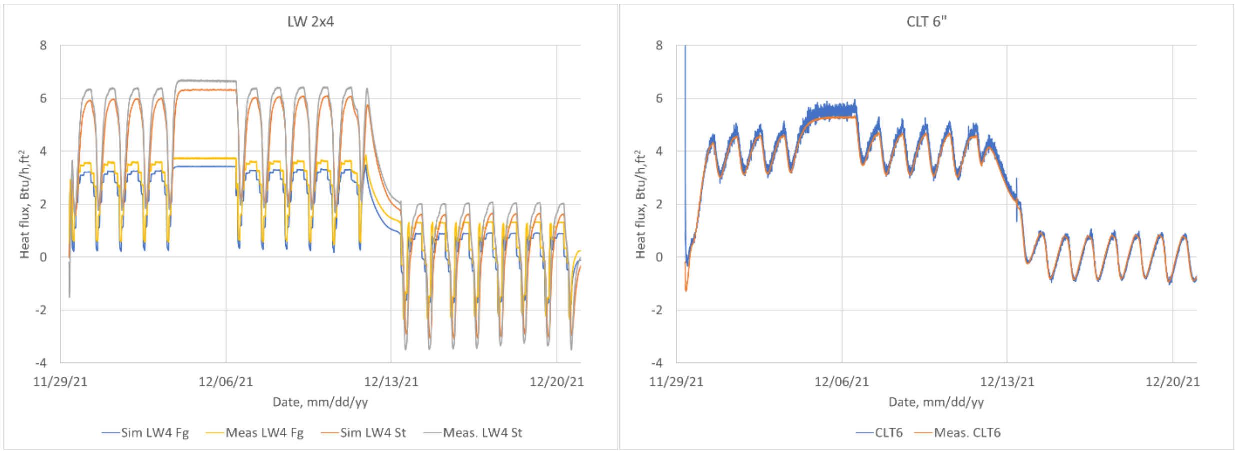

Figure 1 Comparison of measured (Meas) and simulated (Sim) heat fluxes through the lightweight wall (Left, 2x4, LW4) and the 6 ¾in CLT wall (Right, CLT6). LW4_Fg = Heat flux through the center of the cavity, LW4_St = Heat flux through the stud area in the 2x4 wall.

Effective material properties for EnergyPlus simulations

The wall assemblies in the laboratory tests have only wall cavities with one stud in the plain wall area. The average number of studs per wall surface area in actual construction is larger than in the plain wall area. Headers, top and bottom plates, double studs, jack studs, and blockings, among others, increase the amount of thermal bridging in the building envelope. The effect of lumber on thermal performance is considered in energy calculations using a Framing Fraction (FF). The framing fraction is the fractional area of walls, ceilings, floors, roofs, and other enclosure elements comprising the structural framing elements with respect to the total gross area of the component. Default values for the framing fraction in standard walls are 23% for 2x4 walls (frame spacing 16in (406 mm) o.c.) and 20% for 2x6 walls (24in (610 mm) o.c.) (RESNET, 2019).

Energy Plus simulates building envelopes as one-dimensional components with a given area. Therefore, the insulated cavity that includes the lumber as a thermal bridge must be converted from the multidimensional presentation to homogeneous layers. The need is to create effective material properties for a material layer that replaces the cavity's insulation and the wood frame. The materials in the simulated set were (material and thickness): OSB (Oriented Strand Board) 7/16in (11.1 mm), R-13 (RSI-2.3) Fiberglass/Wood stud 3.5in (89 mm) at 16 (406 mm) o.c., and gypsum board ½in (12.5 mm). The material properties used in the calculations are listed in Table 2.

Table 2. Material Properties Used in the Calculations and Effective Properties of Cavities.

Material	**Density, pcf (kg/m³)**	**Heat capacity, Btu/lb,ºF (kJ/kgK)**	**Thermal conductivity, Btu-in/h, ft²,ºF (W/mK)**	**Effective properties, density, pcf (kg/m³) / Heat capacity, Btu/lb, ºF (kJ/kgK)**	**Effective thermal conductivity, Btu-in/h, ft²,ºF**
OSB	31 (496)	0.45 (1.88)	0.763 (0.110)	For fiberglass and wood:	
Fiberglass R-13 (2x4)	0.62 (9.9)	0.20 (0.84)	0.271 (0.039)	15.5 (248)/ 0.20 (0.84)	0.38 (0.055)
Wood	33.7 (539)	0.39 (1.63)	0.694 (0.100)		
Gypsum board	39 (624)	0.21 (0.88)	1.110 (0.160)		

When converting the two-dimensional assembly to one-dimensional, the thermal capacity of the homogeneous material layer was calculated by volume averaging the individual components, thus maintaining the total thermal capacity of the wall. The approach was validated by comparing the transient response of the one- and two-dimensional wall assemblies. Steady-state heat transfer calculations allowed adjusting the effective thermal conductivity for the one-dimensional layer to match the heat flow of the two-dimensional assembly.

IMPACT OF MASS WOOD ON PEAK DEMAND AND ENERGY USE

The whole building simulation model EnergyPlus^{TM} v9.6 (DOE 2021a) was used to evaluate the impact of mass timber wall assemblies on the energy use, peak demand, and thermal comfort of the DOE prototype residential building (DOE 2021b). The DOE prototype building following the IRC 2021 energy code (ICC) used in the simulations is a two-story, single-family building on a slab. The heating and cooling are provided by a heat pump. The conditioned window-to-wall ratio is 15%, with a conditioned floor area of 2377 ft^2. Hygroscopic materials, such as wood, are known to balance indoor air humidity and provide improvements in comfort and energy use (Simonson, 2001). However, our simulations are thermal only, i.e., the moisture effects of wooden structures were not considered.

Simulations were carried out in three IECC climate zones (location): 2A (Houston, TX), 3B (Los Angeles, CA), and 5B (Golden, CO). The DOE prototype building and its lightweight walls were used as the baseline. The exterior wall assemblies were slightly modified for thermal properties to meet the IRC 2021 requirements for lightweight wood frame and mass timber walls. The IRC 2021 building code requirement for the building envelope has two paths: U-factor requirements and the R-value alternative (Table 3). Mass walls were modeled based on the U-factor and the R-value alternative methods.

Table 3. IRC 2021 Building Envelope Requirements

	U-factor, Btu/h,ft^2,ºF (W/m^{2}K)		R-value alternative, h,ft^2,ºF/Btu (m^{2}K/W)	
Climate zone	**Wood frame**	**Mass wall***	**Wood frame**	**Mass wall****
2A	0.084 (0.477)	0.165 (0.937)	R-13 (RSI-2.3)	4/6 (0.7/1.1)
3B	0.060 (0.341)	0.098 (0.556)	R-20 (RSI-3.5) or R-13+5 (RSI-2.3+0.88)	8/13 (1.4/2.3)
5B	0.045 (0.256)	0.082 (0.466)	R-20+5 (RSI-3.5+0.88) or R-13+10 (RSI-2.3+1.76)	13/17 (2.3/3.0)

* The code states that mass timber is considered a mass wall; any wall having a heat capacity greater than or equal to 6 Btu/ft^2,ºF (122 kJ/m^{2}K) is also considered to be a "mass wall."

**4/6, etc., the second value (6) applies if over 50% of insulation is on the interior side of the wall.

The material layers, effective thermal properties and the resulting U-factors are listed in Table 4 when using the U-factor path for compliance.

Table 4. U-factors for Baseline (Wood Frame = WF), Solid (MT) and Exterior Insulated Mass Timber Walls (MTwCI, ci=continuous insulation with R-4.3/in).

Climate Zone/ Wall	2A WF	2A MT	2A MTwCI	3B WF**	3B MT	3B MTwCI	5B WF**	5B MT	5B MTwCI
U-value, Btu/h,ft^2,ºF (W/m^{2}K)	0.083 (0.471)	0.121 (0.687)	0.080 (0.454)	0.062 (0.352)	0.096 (0.545)	0.059 (0.335)	0.047 (0.267)	0.081 (0.460)	0.047 (0.267)
IRC 2021 U-value req.	0.084 (0.477)	0.165 (0.937)		0.060 (0.341)	0.098 (0.556)		0.045 (0.256)	0.082 (0.466)	
Thickness, Mass Timber/ci, in (mm)		6in/0in (152/0)	6in/1in 152/0)	-	7.8in (198)	6in/2in (152/51)	-	9.45in (240)	6in/3in (152/76)

*Framing fraction

**Passes the building code through prescriptive R-value alternative

Finally, one more set of walls was simulated for comparison purposes: The baseline building walls were set to have R-100 continuous insulation to create an extreme case where walls would have practically no heat loss or gain.

ANNUAL ENERGY USE

Table 5 shows the simulated annual heating, cooling, and total energy consumption relative to the base case (lightweight walls). The mass timber walls have equal or lower energy consumption in warmer climates (Houston, TX, and

Los Angeles, CA). In climate zone 5 (Golden, CO), the solid mass timber wall (MT) has a 72% higher U-value, which results in more heating demand during winter months, increasing the annual energy use. The mass timber walls have lower energy use for cooling in all cases except for the solid mass timber wall (MT) in Houston, TX, where the cooling energy use was 101% of that of the baseline case (heating in mass timber building was 1% lower resulting in equal total energy use).

Table 5. Annual Energy Savings of Mass Wood and Extremely Insulated Walls (H=Heating, C=Cooling, T=Total)

CZ, Location	MT, H	MT-wCI, H	MT, C	MT-wCI, C	MT, T	MT-wCI, T	R-100, H	R-100, C	R-100, T
2A, Houston, TX	1%	11%	-1%	6%	0%	8%	2%	16%	20%
3B, Los Angeles, CA	9%	23%	22%	18%	15%	19%	41%	6%	19%
5B, Golden, CO	-17%	0%	12%	11%	-12%	2%	18%	2%	16%

PEAK DEMAND AND MASS TIMBER

The peak demand was evaluated by looking at the typical hourly heating (H) and cooling (C) demand and heat flow through walls each month. The hourly data were averaged to create a typical day profile for each month. Reducing the peak demand or shifting the demand to other times away from the common peak hours would reduce energy costs and help the grid balance the energy demand and supply. Additionally, the heat flows through all walls were summed up for each hour on the interior surface of the walls, and a typical heat flow profile was created for each month.

The graphs in Figure 2 show the heating, cooling, and summed-up heat flows through all the walls on a typical day in January and July, as appropriate.

The mass timber walls (solid mass timber and exterior insulated mass timber) reduce the peak demand and dampen the minimum-maximum heat flows in all cases, except for heating demand in Golden, CO, where the heating demand is higher with the solid mass timber walls than with the insulated walls. That is due to the 72% higher U-value of the solid mass timber wall than those of the insulated walls (LW and MT-wCI). The thermally massive walls (MT and MT-wCI) shift cooling demand away from the afternoon peak hours to earlier in the day in all climates.

IMPACT OF MASS WOOD ON THERMAL COMFORT

The DOE prototype residential building has only one zone, i.e., the interior of the building is not divided into rooms that could be individually controlled and evaluated. Comfort conditions in a building can be different in rooms that face different orientations due to solar radiation effects. Thus, the comfort calculations represent average conditions in the whole building.

Table 6 shows the hours in the annual simulations when the comfort conditions were not met. “Time Not Comfortable Based on Simple ASHRAE 55-2004” table shows how many hours the space is not comfortable for each zone. “Time Setpoint is Not Met table” shows how many hours the space is more than 0.2ºC from the setpoint during heating and during cooling.

The Adaptive Comfort Summary in EnergyPlus produces a report tabulating the sum of occupied hours not meeting adaptive comfort acceptability limits. The 90% acceptability limit ASHRAE Std. 55-2010 is used here.

The “Time not comfortable based on simple ASHRAE 55-2004” values show that the mass timber walls generally improve thermal comfort by lowering the number of hours when the conditions are not comfortable. Solid mass wall (MT) reduces the uncomfortable hours by 31% in Houston, TX, and 46% in Los Angeles, CA. In Golden, CO, the significantly higher U-value causes the walls to be cold enough to provide 35% more discomfort hours. The exterior insulated mass timber wall MT-wCI has 30%, 32%, and 19% fewer discomfort hours in Houston, TX, Los Angeles, CA, and Golden, CO, respectively.

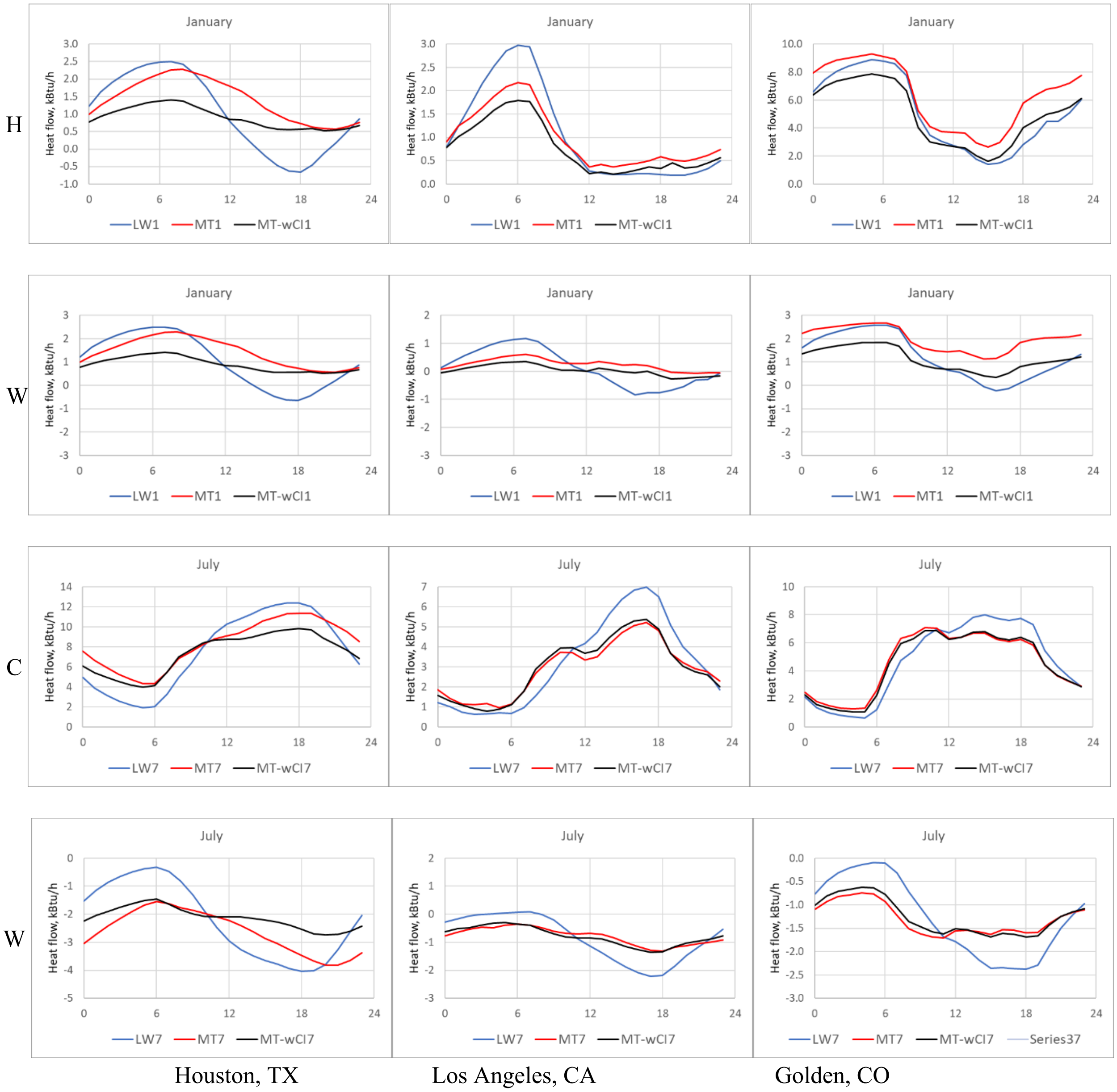

Figure 2 Typical hourly heating (H), cooling (C), and wall heat flow (W) profiles (sum of all orientations) in Houston, TX, Los Angeles, CA, and Golden, CO (from left to right). LWn=lightweight wall, MTn=solid mass timber wall, MT-wCIn=Mass timber wall with continuous insulation. The number “n” tells the month of the year.

Table 6. Hours When Comfort Conditions Were Not Met in Annual Simulations.

		Houston, TX	Los Angeles, CA	Golden, CO
Time Setpoint Not Met During Occupied Heating	Base	8	1	54
	MT	0	3	71
	MT-wCI	2	4	56
Time Setpoint Not Met During Occupied Cooling	Base	388	13	36
	MT	324	1	43
	MT-wCI	415	7	42
Time Not Comfortable Based on Simple ASHRAE 55-2004	Base	2502	426	816
	MT	1727	229	1104
	MT-wCI	1747	291	664
ASHRAE55 90%-2010 Acceptability Limits [Hours]	Base	420	46	195
	MT	103	0	139
	MT-wCI	72	0	159

CONCLUSION

This research study evaluated the impact of mass timber on energy use, peak demand, and thermal comfort in buildings. Laboratory tests were first conducted in the Large Scale Climate Simulator at ORNL to validate the modeling of the thermal response of actual wall assemblies. Then effective material properties were created to enable simulation of the assemblies using a whole building simulation model (EnergyPlus) in three climate locations.

The results show significant impacts of the thermal inertia of the mass timber wall assemblies on the annual energy use and especially on the peak demand compared to the standard 2x4 and 2x6 lightweight wall systems. In this study, the annual energy savings with mass timber walls compared to the baseline lightweight walls depending on the climate zones were up to 22%. The solid mass wall with a 72% higher U-value than the baseline wall had 12% higher heating and cooling energy use than the baseline wall in Golden, CO. The lightweight walls with extreme insulation levels (R-100 continuous insulation) did not save as much cooling energy as the mass timber walls. The result shows that when the focus is on lowering the cooling energy use, more insulation is not necessarily the solution; instead, adding thermal mass should be considered.

Mass timber walls efficiently shifted heating and cooling energy demand to other hours away from the peak demand hour, thus helping the grid. As a result, the peak demand for heating and cooling was 30%-50% lower with mass timber, depending on the month and location.

Finally, based on the simulations, mass timber walls were shown to improve thermal comfort by reducing the not-comfortable hours by up to 46%.

DISCUSSION

This work created new knowledge about the efficient use of mass timber structures to improve the energy performance of buildings and can lead to an increase in the use of mass timber to build energy-efficient buildings.

The research will continue in a follow-up project to evaluate how thermal comfort can contribute to new findings associated with energy-saving in mass timber buildings by maintaining thermal comfort inside of the living space instead of applying fixed temperatures. That could reduce the required wall thicknesses of mass timber buildings, thus potentially lowering the embodied carbon overall. Ultimately the research will support the decarbonization of buildings by supporting the use of mass timber in buildings.

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REFERENCES

ASHRAE (2004) ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy. American Society of Heating Refrigerating and Air-Conditioning Engineers, Atlanta.

COMSOL Multiphysics® v. 5.1. www.comsol.com. COMSOL AB, Stockholm, Sweden.

DOE 2021a. "EnergyPlus Energy Simulation Software." Washington, DC: US Department of Energy. www.energyplus.net.

DOE 2021b. "Prototype Building Models. Residential." Washington, DC: US Department of Energy. https://www.energycodes.gov/prototype-building-models

Grand View Research. 2021. https://www.grandviewresearch.com/industry-analysis/cross-laminated-timber-market. Accessed 04/12/2022.

ICC. 2021 International Building Code (IBC). ICC International Code Council, Inc. 500 New Jersey Avenue NW, 6th Floor, Washington, DC 20001. codes.iccsafe.org.

ICC. 2021 International Residential Code (IRC). ICC International Code Council, Inc. 500 New Jersey Avenue NW, 6th Floor, Washington, DC 20001. codes.iccsafe.org.

RESNET. ANSI/RESNET/ICC 301-2019, Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index. Residential Energy Services Network, Inc. http://resnet.us/

Simonson, C. J., Salonvaara, M., & Ojanen, T. (2001). Improving indoor climate and comfort with wooden structures. Technical research centre of Finland. VTT Publications (431).

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