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

Mikael Salonvaara
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FINAL REPORT

OAK RIDGE
National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

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Buildings and Transportation Science Division

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Prepared by
OAK RIDGE NATIONAL LABORATORY
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ACKNOWLEDGMENTS

This CRADA NFE-20-08326 was conducted as a Technical Collaboration project within Oak Ridge National Laboratory's (ORNL's) Building Technologies Research and Integration Center. The goal of technical collaborations is to provide small businesses and other industry partners access to ORNL's Building Technologies Research and Integration Center (BTRIC), where they can undertake collaborative, short-term research projects that accelerate the development of new energy-efficient building technologies. This opportunity, funded by the US Department of Energy's (DOE's) Building Technologies Office (BTO), gives selected participants access to ORNL's experienced staff, unique equipment, and research capabilities.

This project was carried out in partnership with the International Mass Timber Alliance (IMTA) who provided the cross-laminated timber panels used in the projects. Technical support to the project from Mr. Robert Pickett, IMTA secretary, and Dr. Carl Manz, CT Manz Consulting, Inc., is greatly appreciated.

ABSTRACT

Thermal mass moderates indoor temperatures, allowing heating, ventilation, and air conditioning (HVAC) systems to operate more efficiently during peak hours. Cross-laminated timber (CLT) and other mass wood products provide thermal mass to the building envelope in a lighter and more environmentally friendly form than concrete. However, the influence of CLTs on heating and cooling energy, peak energy demand, and the indoor climate is not well known. This project was initiated to identify the energy efficiency benefits of mass timber structures. The objectives were to (1) test the thermal performance of insulated mass wall structures in controlled laboratory conditions, (2) validate simulation models to expand performance to natural climatic conditions, (3) isolate the impact of the thermal properties of wood (thermal mass, thermal conductivity, moisture storage) on heating and cooling energy use and peak energy demand, as well as 4) to optimize the performance. Currently, the designs used for CLT buildings focus on structural and fire issues, and they do not consider the thermal mass benefits. Therefore, the thermal performance is not necessarily optimized.

1. INTRODUCTION

1.1 BACKGROUND

Homes with solid mass wood walls (MWW) represent 1.5% of all new home starts and 7% of custom home starts in the United States. The MWW market in the United States has risen from nearly \$65 million to over \$170 million in 2019 and is projected to reach nearly \$400 million by 2025.

By application, the cross-laminated timber (CLT) market is segmented into residential buildings, educational institutions, government/public buildings, and industrial and commercial spaces. Residential buildings held the largest market share in 2017, at around 50%. The demand for wooden residential buildings, including multifamily apartments and single-family homes, is rising. In addition, CLT homes' earthquake resiliency (Morrison Maierle, 2021) improved fire resistance qualities, and embodied carbon benefits are anticipated to drive the market in the coming years.

The roughly 200 members of the International Mass Timber Alliance (IMTA), a Tennessee association, produce residential and commercial mass timber construction. The IMTA was formed in 2017 to perpetuate mass wood building on a global scale. It operates to expand scientific evidence as to the performance of mass wood so as to translate that evidence into language that can be adopted into codes and standards.

CLT-based buildings take less time to construct; because mass timber panels are prefabricated, smaller crews can assemble structures more safely and 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 the use of CLT and other innovative engineered wood materials in taller buildings. Fourteen mass timber code change proposals were recently approved, clearing the way for their inclusion in the 2021 International Building Code (IBC). 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 stories tall. However, guidance for thermal design to make the best use of the thermal mass in mass wood structures 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 day times.

1.2 OBJECTIVES

The project goal is to obtain data to inform opportunities to further improve the thermal efficiency of buildings' envelopes by measuring the thermal performance of mass-timber (MWW) structures. This study provides input to building heating and cooling energy simulations to demonstrate thermal performance benefits (total energy, peak demand) when mass timber is substituted for standard framed systems. We estimate up to 50% lower cooling energy use during peak cooling hours due to the thermally optimized MWW structure's time shift of heat gains. These savings can translate into significant cost savings when time-of-use rates are applied.

1.3 BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

This CRADA project helps develop a method to quantify the energy benefits of mass timber structures. The tools proposed in this research address energy and peak demand reduction.

This research proposes to provide novel tools supporting this new and emerging mass timber industry. Indirectly, the most efficient use of mass wood can be designed by the ability to assess the effective thermal performance for cooling and heating. The optimal use of mass wood requires understanding how much wood is effectively necessary for thermal and structural performance.

Domestic mass timber producers and emerging CLT producers represent beneficiaries of the assessment and design tools to be developed by this research. Producers must be able to present scientifically assessed material to market these products efficiently and provide code institutions with demonstrated performance claims. In addition, homeowners purchasing CLT homes will benefit from improved energy efficiency and a more comfortable environment.

2. TECHNICAL WORK

The approach taken in the project included the following tasks:

1. State-of-the-art review of wood as thermal mass.
2. Modeling of lightweight and mass wood structures to design laboratory testing scenarios and assembly details, such as the order and thicknesses of insulation and mass wood layers.

3. Wall assembly testing in a climate chamber for model validation and thermal impact demonstration.
4. A screening simulation study of the effect of mass wood assemblies on the hourly peak demand and energy use of a residential building.
5. Summary report.

After the state-of-the-art review, the two main tasks in the project were to conduct laboratory testing to validate a simulation model (EnergyPlus) and then use the validated model to evaluate the impact of mass timber on peak demand and energy use of a residential building.

2.1 LITERATURE REVIEW

Mass timber is a framing style typically characterized by large solid wood panels for wall, floor, and roof construction. Some of these products include solid logs fastened together (as used in log houses), glue-laminated timber (glulam), CLT, laminated strand lumber (LSL), laminated veneer lumber (LVL), nail-laminated lumber (NLT), and other large-dimensioned structural composite lumber (SCL) products.

Mass timber is an engineered wood product of large section size that offers a viable alternative to steel and concrete (Carbal & Blanchet 20121, Harte 2017). CLT, also known as *X-lam*, is the most commonly used mass-timber product (Harte 2017, Brandner et al., 2016). Several works reported on mass timber buildings' performance with respect to structural integrity (Mayo 2015, Wang JY et al. 2018, Wang JB et al. 2018, Oliveira 2018, Ringhofer et al. 2018), sustainability, and environmental impacts (Gustaveson et al. 2006, Dewsbury et al. 2016, Dong et al. 2019, Cascone et al. 2018-a & 2018-b), and moisture durability performance (Kordziel et al. 2019, Shirmohammadi et al. 2021, Riggio et al. 2019, Schmidt and Riggio 2019, Setter 2019, Wang 2019) are reported on timber wall buildings. But as pointed out by Carbal and Blanchet (2012), the thermal performance of mass timber wall systems has not been investigated in detail. Jensen et al. (2020) pointed out many claims of timber's ability as thermal mass, despite an apparent gap in substantive literature quantifying this behavior in timber.

Thermally massive buildings such as masonry (Gagliano et al. 2014), highly insulated wood frame walls (Aste et al. 2009), and wood-frame walls with an added sand in the cavity (Tonelli and Grimaudo 2014) can provide a useful thermal mass that can help reduce overheating, increase energy savings, and shift peak-load demand. A typical CLT residential home has 2–5 times more thermal mass than that of traditional lightweight construction (Setter 2019).

The current literature on thermal storage capacity and thermal performance of mass timber wall systems is reviewed and presented below.

Szalay (2004) used the analytical calculation of a time constant of a solid timber wall using EN 832:1998. Time constants of the solid timber wall are compared against buildings with timber frames, timber frame and adobe wall, clay block, and aerated concrete. According to the calculations, the time constant of solid timber buildings is the highest, followed by clay block, whereas aerated concrete and timber frame are in the same range.

Dewsbury et al., in their previous simulation research, found significant thermal performance benefit when mass timber elements were added to the built fabric (roof, external walls and other components separating indoor and outdoor environments) (Dewsbury, Geard, et al. 2012, Dewsbury 2013, Dewsbury, Tooker, et al. 2013). Dewsbury et al. (2016) conducted a field test and empirical evaluation of the performance of mass timber as partition walls and flooring. Their findings produced results that confirmed the ability of mass timber to act as a thermal capacitor and as an additional insulator, to reduce general heating and cooling energy loads, and to reduce peak heating and cooling energy loads.

Furthermore, the measured thermal performance of the mass-timber partition walls and mass-timber flooring strongly matched the simulated thermal performance. The strong correlation between the empirical and simulated data supports the hypothesis that mass timber does provide effective thermal mass within buildings. Within this context, research has shown that carefully placed mass-timber elements within the built fabric of buildings provide a pathway to lightweight, low-carbon, and high thermal performance timber buildings. In addition, the paper discusses the potential of mass-timber products within the built fabric to provide improved thermal performance for a relatively small increase in embodied energy, as well as to significantly improve long-term carbon sequestration.

Marjakangas (2014) researched the actual energy consumption in log houses and compared the results to calculated values. The study performed for 80 mass wood buildings in Finland showed up to a 50% lower measured actual heating demand than the calculated heating demand. Part of the study was to determine the reasons for differences between the actual and calculated values. In the study, they gathered research material from the residents through surveys. Then, they standardized the energy consumption to one location (Jyväskylä). The results indicated that the energy efficiency of log houses is better than what is presumed in the regulations, and on average, the energy consumption is lower than calculated. They also noted that the actual consumption of energy in most subjects is much smaller than the calculated value. It seemed that the different resident habits had a large impact on the performance, and the actual energy consumption alternated largely between the study subjects. They concluded that a greater number of subjects and measurements could improve the reliability of the results.

Setter et al. (2019) studied the energy and hygrothermal performance of CLT in residential buildings using BEopt, EnergyPlus, and WUFI tools. They evaluated two buildings with the same thermal mass but different airtightness for annual energy use and peak demand. Based on their previous work (Khavari et al., 2016), CLT buildings demonstrate improved airtightness, and airtightness of 2 ACH50 was used in this study. Their results show that the use of CLT in the construction of single-family homes results in annual energy cost savings of up to 18% in the five climates considered. Peak demand was reduced by up to 20%: half of this improvement was due to the inclusion of thermal mass of CLT, and the other half was due to improved airtightness of the CLT structures. The simulations showed that the energy savings due to airtightness were more significant in comparison to thermal mass in cold climates than in warm climates.

Yin and Lee (2019) used the EnergyPlus simulation of the 10-story US Department of Energy (DOE) benchmark residential building to evaluate the residential buildings' energy consumption and peak load with CLT, CLT concrete, and concrete. Different locations in the Canadian climate were used in this study. There was no significant difference between buildings with different structural systems in Montreal QC, Toronto ON, and Vancouver BC for the heating load. For the annual heating/cooling energy consumption, the concrete system consumed around 2% to 7% less than the CLT and hybrid system. There was no significant difference between CLT and the hybrid system. The difference of the peak load and annual energy consumption of the buildings with different structural systems in Vancouver was more significant than that in Montreal and Toronto.

Dong et al. (2019) compared the CLT system for office buildings to similar buildings with reinforced concrete structures to study the energy-saving potential in China's five different climate zones. Results show significantly higher heating energy reductions for CLT buildings in China's cold and severe cold regions. Based on their results, the application of CLT walls in cold areas is recommended. However, in terms of thermal mass and thermal comfort in the summer, CLT underperformed compared to concrete walls. The CLT system also increased the cooling energy requirements in summer, thereby increasing the possibility of overheating in CLT office buildings. The authors concluded that "CLT may not be such a good alternative building material for regions, namely the Temperate Region and Hot-Summer Warm-Winter Region without considerable heating requirements."

Tettey et al. (2019) claimed that the CLT and modular building systems result in lower primary energy use for material production and construction than concrete alternatives. Their results also showed that CLT required between 20% and 37% less energy than concrete for heating and cooling.

Jensen et al. (2020) attempted to study the extent to which mass timber is thermally massive compared to wood stud and concrete construction and how this behavior contributes to a building's life cycle carbon. The authors conducted energy simulations and life cycle assessments for the daily decrement in peak temperature, annual cooling energy and overheating hours, and life cycle carbon. By taking into account cooling energy, decrement, and air-conditioning delay, the mass timber design provides half the thermally massive benefits of a concrete design of equal size. Their findings also show a 93% reduced embodied energy by mass timber when compared to concrete for both the cities of Los Angeles and Seattle. The life cycle carbon (sum of embodied and operational) was reduced by as much as 27% and 60% to concrete in Seattle and Los Angeles, respectively.

Adekunle (2021) monitored a CLT school building's thermal performance in the New England region during the summer. The development was occupied from 8 am to 6 pm and partly operated from 7 pm to 7 am during the survey. The mean temperatures during the occupied and non-occupied periods varied from 22.1°C–22.4°C. The overall relative humidity was 59.2%. The predicted mean vote (PMV) range and sensation showed the occupants were comfortable. Approximately 80% of the users were satisfied with the thermal environment. The results did not suggest the occurrence of summertime overheating and heat stress within the spaces.

Rodrigues et al. (2016)—though not analyzing a solid timber wall system—used eight fully prefabricated timber cassette panel structures filled with glass wool insulation and application of phase change material (PCM) to reduce building energy demand. They compared the wall system with concrete of the same thickness. Adding the glass wool and PCM reduced the overheating to some extent. Concrete with the same thickness as the layers of glass wool was found to be slightly more effective in reducing overheating.

Carbal and Blanchet (2021) conducted an exhaustive literature review on the overall energy efficiency of wood buildings. This article dedicates a section for mass timber walls, and four reports are reviewed. All four of the studies report the energy-saving potential of mass timber walls.

Studies from the 1980s, such as a study conducted by the former National Bureau of Standards (NBS) (today's National Institute of Standards and Technology, or NIST, since 1988), to determine the effects of thermal mass (the bulk of solid wood log walls, or brick and block walls) on a building's energy consumption, found the log building to use 46% less heating energy than the insulated wood frame building during a three-week spring heating period (Burch et al. 1982). During the eleven-week summer cooling period, the log building used 24% less cooling energy than the insulated wood-frame building. During the fourteen-week winter heating period, the log building and the insulated wood frame building used virtually identical amounts of heating energy. The mass wood wall was a 7 in. thick solid square log providing a nominal R-10 h,F,ft^2/Btu. The wood frame 2×4 stud wall was rated at nominal R-12, i.e., a 17% higher R-value than the mass wall. During the entire 28-week test cycle, including three seasons, both buildings used approximately the same amount of energy. NBS concluded that the thermal mass of log walls is an energy-conserving feature in residential construction.

This study supplements the past work focusing on field studies by carrying out a laboratory experiment followed by simulations. The simulation model is first validated against laboratory experiments to ensure the model's ability to characterize the assembly performance at the component level in dynamic conditions. Then, the validated model is used to evaluate a whole building with different wall components in different climates. The results are then analyzed for energy use, peak demand, and thermal comfort conditions.

2.2 LABORATORY TESTS TO COMPARE MASS TIMBER AND LIGHTWEIGHT WALL STRUCTURES

2.2.1 Thermal performance measurements in the Large-Scale Climate Simulator

The test chamber used in this study was ORNL's Large-Scale Climate Simulator (LSCS). The simulator allows for controlling the exterior climate on the upper chamber and indoor climate on the lower chamber. The chamber can be run with a metering chamber (as shown in Figure 1) to measure heat flow through the assembly. However, we tested four wall samples simultaneously; therefore, heat flux transducers were used instead of the metering chamber.

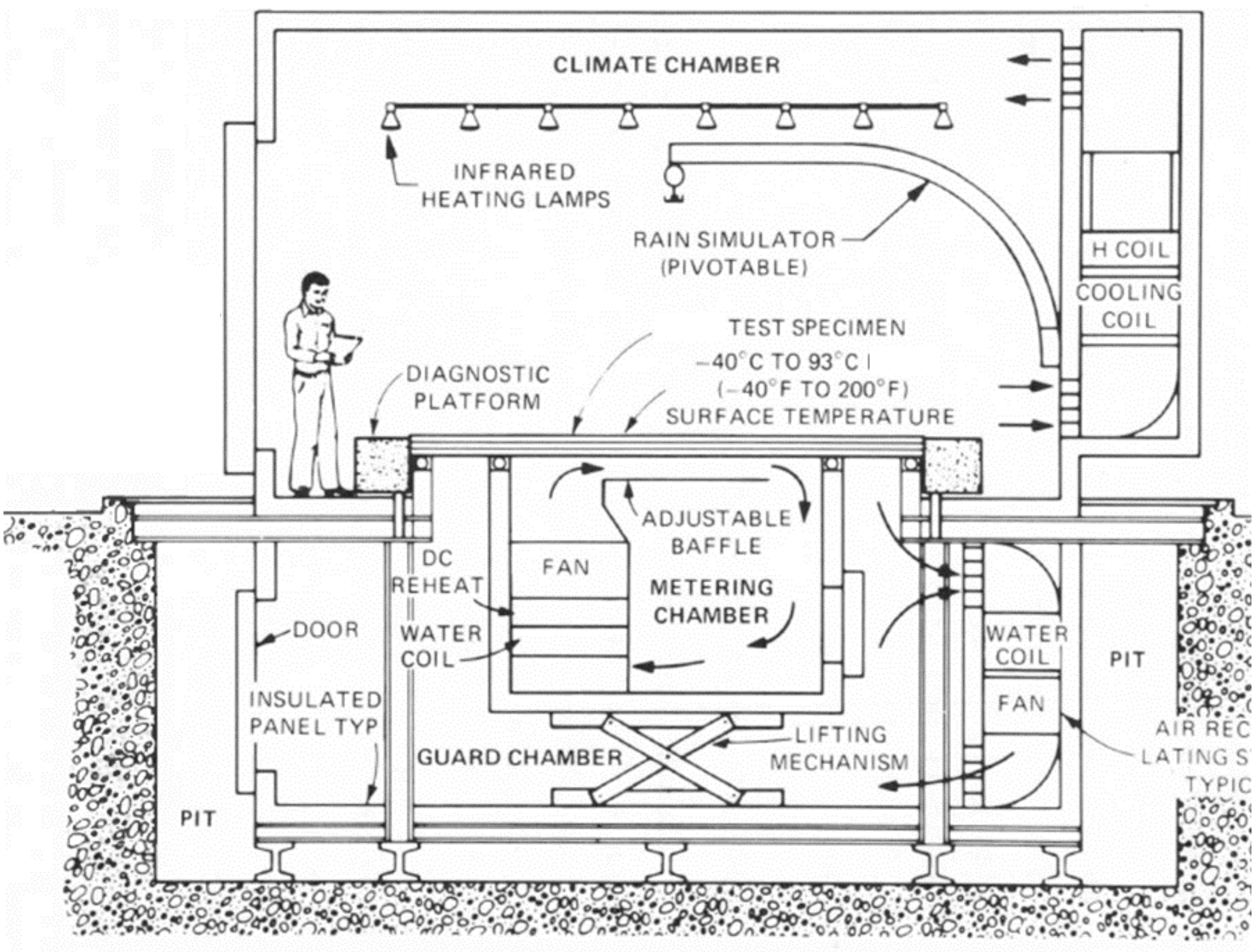

Figure 1. Schematic drawing of ORNL's Large Scale Climate Simulator (LSCS).

2.2.2 Test assemblies

Table 1 lists the four test assemblies constructed and assembled in the test frame for the LSCS. The CLT wall panels were provided by the International Mass Timber Alliance and delivered to ORNL. The walls included two lightweight walls (2×4 and 2×6) and 4 in. and 6 ¾ in. CLT walls. The 2×4 lightweight wall had R-13 fiberglass batt insulation, and the 2×6 wall had R-23 mineral wool insulation. The exterior surfaces of the walls were painted white to have the same absorptance for the radiation from the heat lamps. All walls had gypsum board on the interior side. Additionally, the lightweight walls had oriented strand board (OSB) as the exterior sheathing. CLT panels were exposed to the exterior environment without OSB.

Table 1. Wall assemblies in LSCS tests.

Wall	Description from indoors to outdoors
2×4 Lightweight	½ in. Gypsum board, R13 batts, studs at 16 in. on center (3.5 in. cavity), 7/16 in. OSB
2×6 Lightweight	½ in. Gypsum board, R23 batts, studs at 24 in. on center (5.5 in. cavity), 7/16 in. OSB
4 in. CLT	½ in. Gypsum board, 4 in. CLT
6 ¾ in. CLT	½ in. Gypsum board, 6 ¾ in. CLT

As shown in Figure 2, the walls were installed horizontally on the frame that was lifted into the chamber. Each wall section was separated by 2 in. of extruded polystyrene insulation.

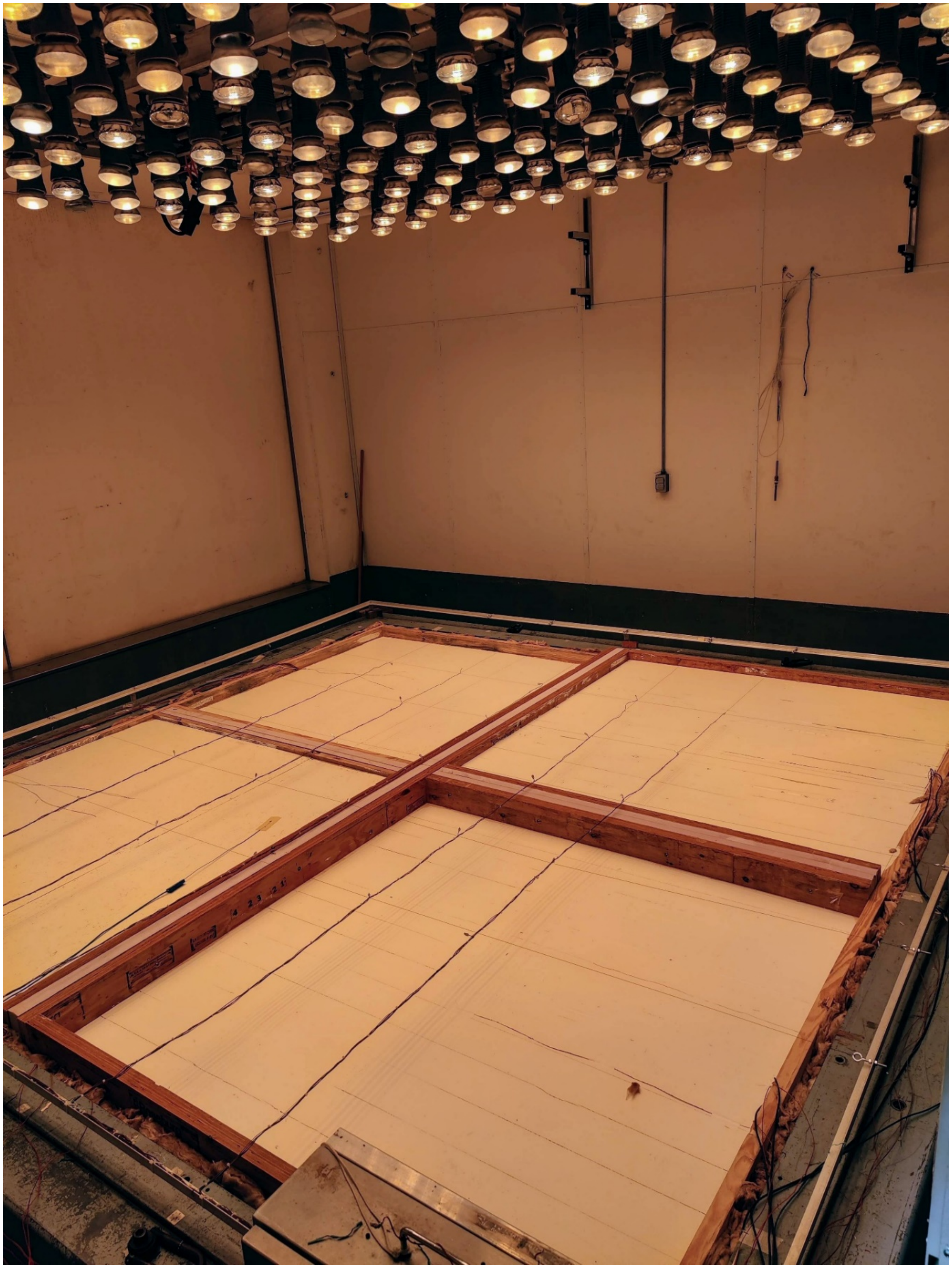

Figure 2. Wall assemblies installed in LSCS. Heat lamps are shown on top.

2.2.3 Selection of the climatic conditions for laboratory testing

Before testing mass timber and lightweight stud wall structures in a climate chamber, we performed simulations to predict the performance of the lightweight and CLT walls under varying climatic conditions to evaluate the test conditions to plan for the chamber testing. The goal was to understand the impact of thermal mass performance and the required time for testing. The purpose of the simulations was to ensure that the test conditions would provide results that allow for proper analysis. These test results were later compared to the simulations to validate the performance of the simulation models. The comparison provided an opportunity to finetune the simulation models if significant differences occurred between the simulated and tested performance.

The weather conditions for the laboratory testing were chosen to be those in Golden, CO, that represent International Energy Conservation Code (IECC) climate zone 5B. Golden, CO, has cold winters and sunny days, providing large temperature swings on walls between night and day. Typical daily temperature and solar radiation profiles were taken for February and August using the TMY3 weather files in EnergyPlus. Temperature and solar radiation (global horizontal radiation) are shown in Figure 3**Error! Reference source not found.**.

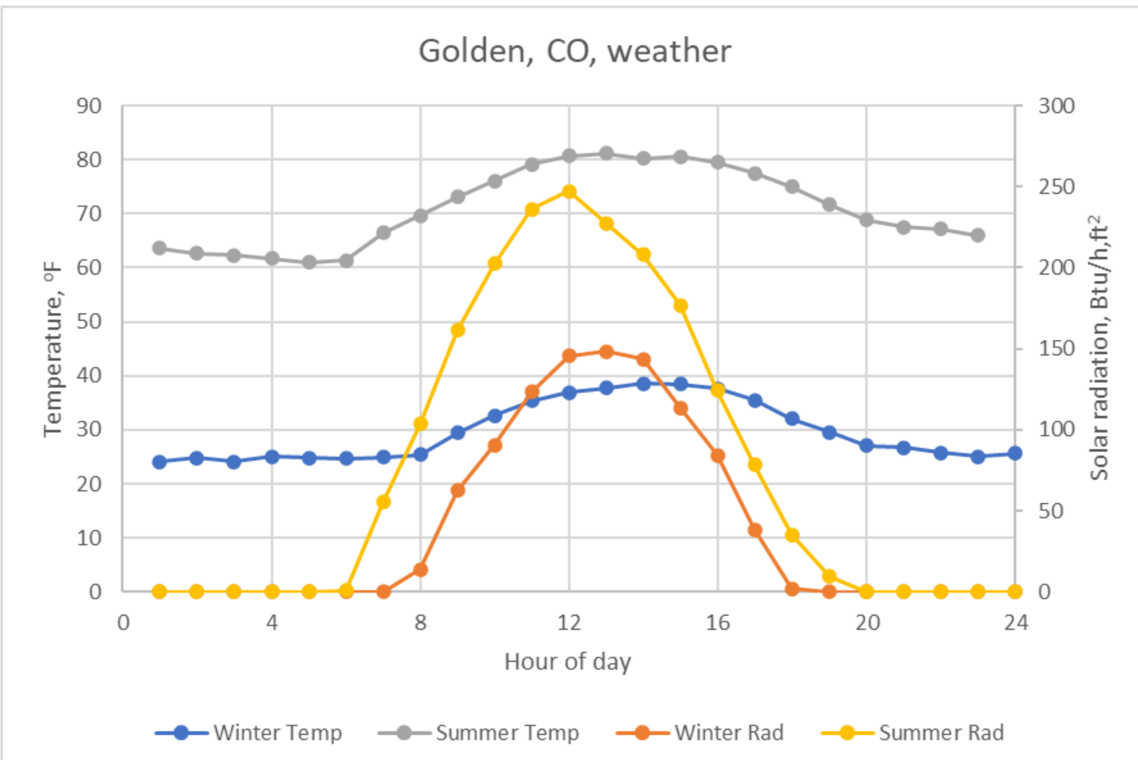

Figure 3. Typical daily temperature and solar radiation in February and August in Golden, CO.

2.2.4 Simulated thermal performance to set control values for laboratory tests

The weather conditions in Golden, CO, **Error! Reference source not found.** were used to simulate the surface temperature on the wall assembly representing the lightweight wall facing south orientation. 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. The surface temperature on the lightweight wall was used to control the heat lamps representing solar radiation. The heat lamps, then, provided the same radiation load on all four samples. The air temperature in the climate chamber was set to 5°F 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 for temperature control. Therefore, the temperature setpoints are shown as steps that do not follow the profile strictly at every hour but supply a reasonable simulation of the diurnal cycle. The indoor conditions were set to constant 69°F.

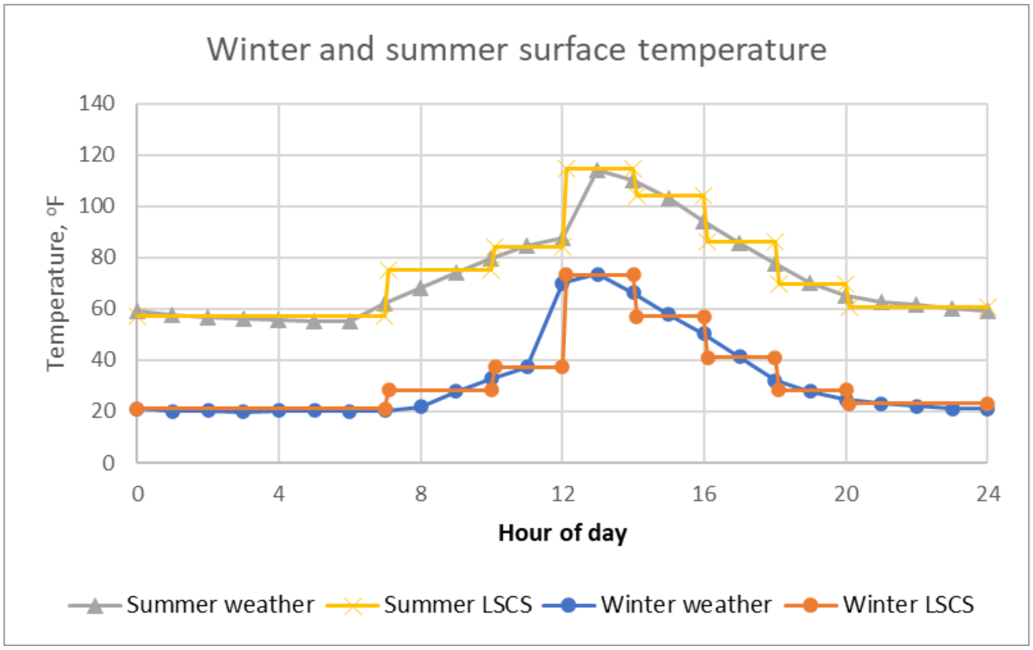

Figure 4. Surface temperature for heat lamp control in the LSCS.

2.2.5 Temperature and heat flux transducers – lightweight walls

The temperature sensors (type T thermocouples) were placed on four planes on the lightweight walls:

1) On the exterior surface
2) Between the oriented strand board (OSB) and fiberglass insulation, and between OSB and stud
3) Between fiberglass insulation and gypsum board, and between stud and gypsum board
4) On the interior surface

The heat flux transducers (Concept Engineering, 2 × 2 in.) were placed between fiberglass insulation and gypsum board and between stud and gypsum board (Figure 5). The sensors were calibrated for use with these material combinations.

Figure 5. Heat flux transducers (Concept Engineering, 2 × 2 in.) as installed between the wood stud and the gypsum board.

2.2.6 Temperature and heat flux transducers – CLT walls

The CLT walls do not have OSB on the exterior and are homogeneous with mass wood instead of insulation and studs. The temperature sensors were placed on three planes:

1) On the exterior surface
2) Between CLT and gypsum board
3) On the interior surface

The heat flux transducers (Hukseflux HFP03) were placed on locations 1 (Figure 6) and 2 above. Factory calibrations were used to calculate the heat flux from their voltage output.

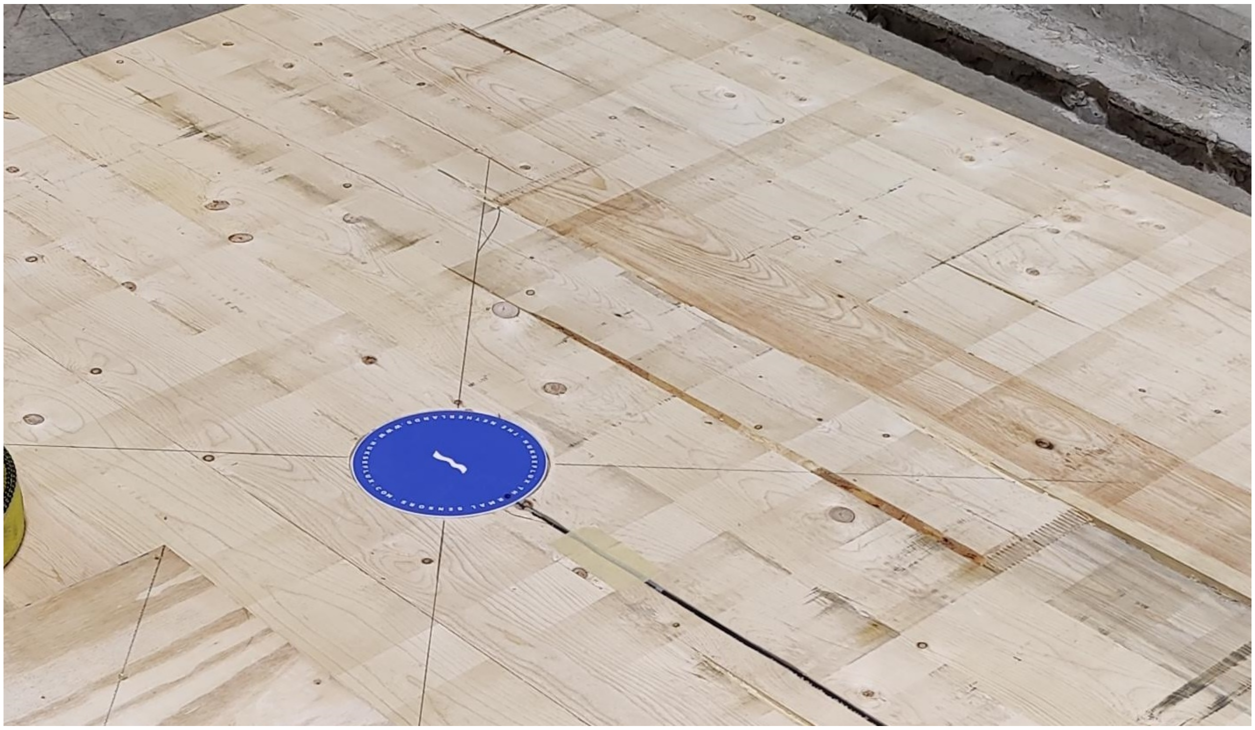

Figure 6. Heat flux transducer (Hukseflux HFP03) on the exterior side of a CLT panel.

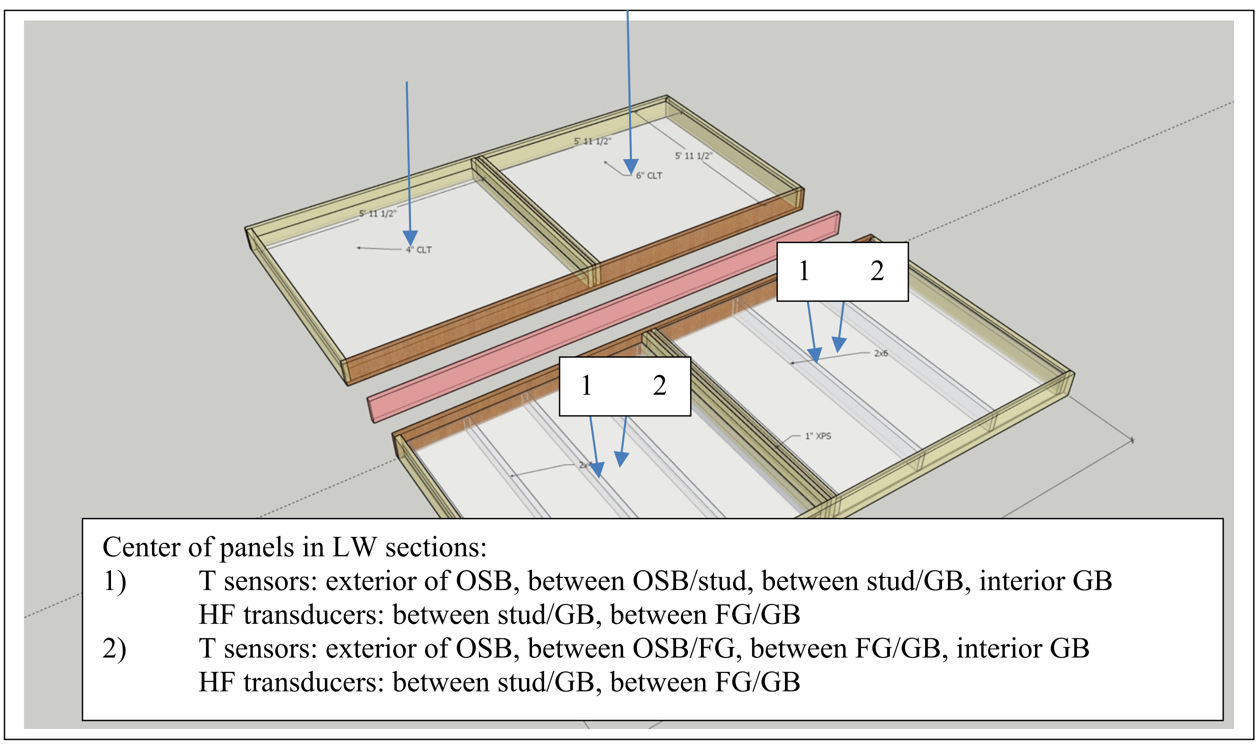

Figure 7. Sensor locations in the wall sections.

2.3 COMPARISON OF MEASURED AND SIMULATED PERFORMANCE IN LABORATORY CONDITIONS

Measurements were collected for approximately one week, repeating the scheduled hourly temperatures in the climate chamber each day. The winter schedule was run first, followed by a stabilization period to reach steady state, followed by the summer schedule.

2.3.1 Test results in winter conditions

Figure 8 shows the air temperatures in the exterior and interior climate chambers, as well as the exterior surface temperature on the 2×6 lightweight assembly in the LSCS during the winter conditions. The indoor air temperature was maintained constant. The temperature in the outdoor (exterior) chamber increased slightly over time during solar radiation due to coil freezing and reduced capacity to cool. However, this had no impact on the test performance. The exterior surface temperature of the samples was controlled to the time-dependent set point using heat lamps, and the heat flux through the sample depends on the exterior surface temperature.

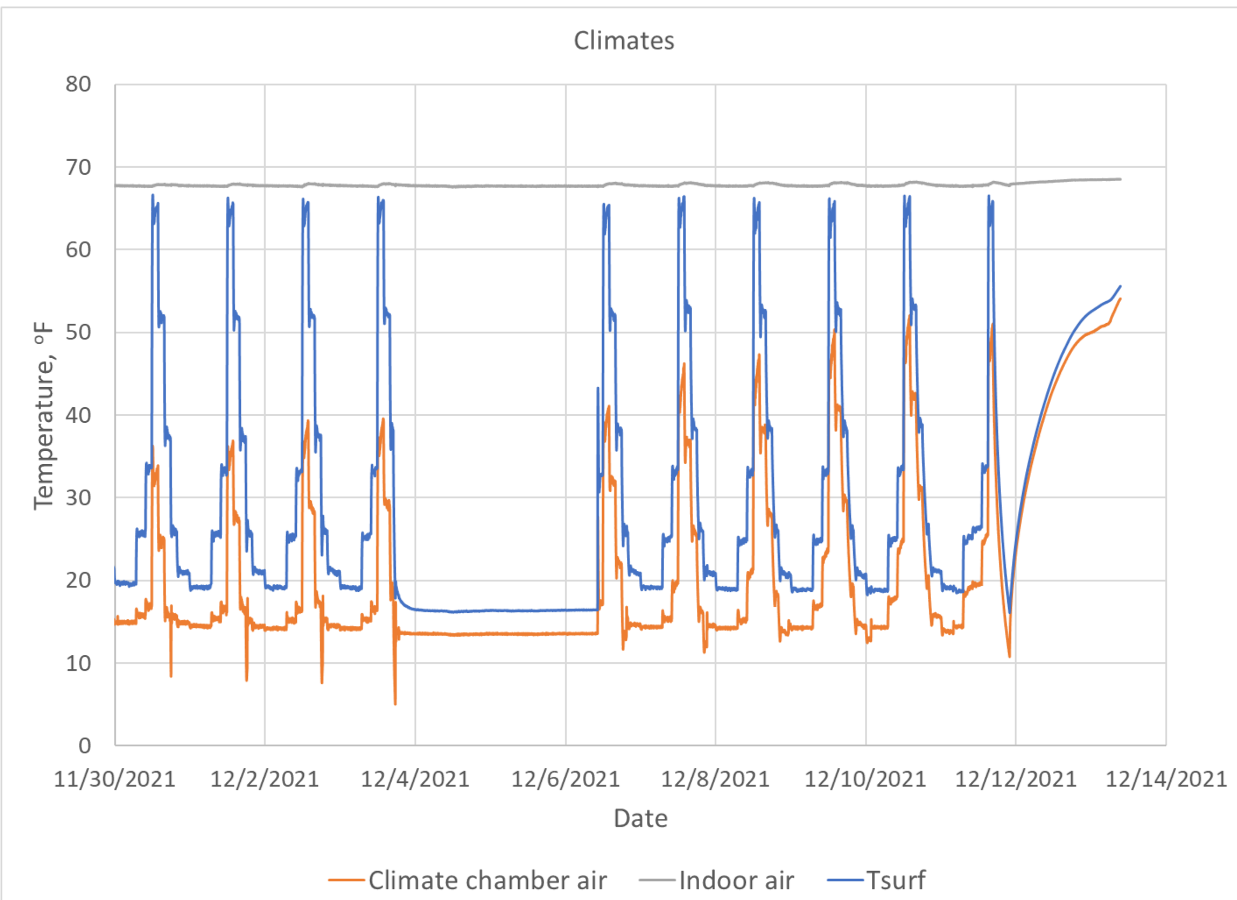

Figure 8. Air temperatures in climate and indoor chamber and the exterior surface temperature of the 2×6 lightweight assembly during testing in winter conditions.

The heat fluxes on the interior surface during testing in winter conditions are shown in Figure 9 and Figure 10.

The naming convention is as follows:

- LW4 and LW6 are lightweight walls of thickness 3.5 in. and 5.5 in., respectively
- CLT4 and CLT6 are mass timber walls of thickness 4 in. and 6 ¾ in., respectively
- St/Gb is the heat flux transducer location between a stud and gypsum board
- Fg/Gb is the heat flux transducer location between fiberglass insulation in the middle of the cavity and gypsum board

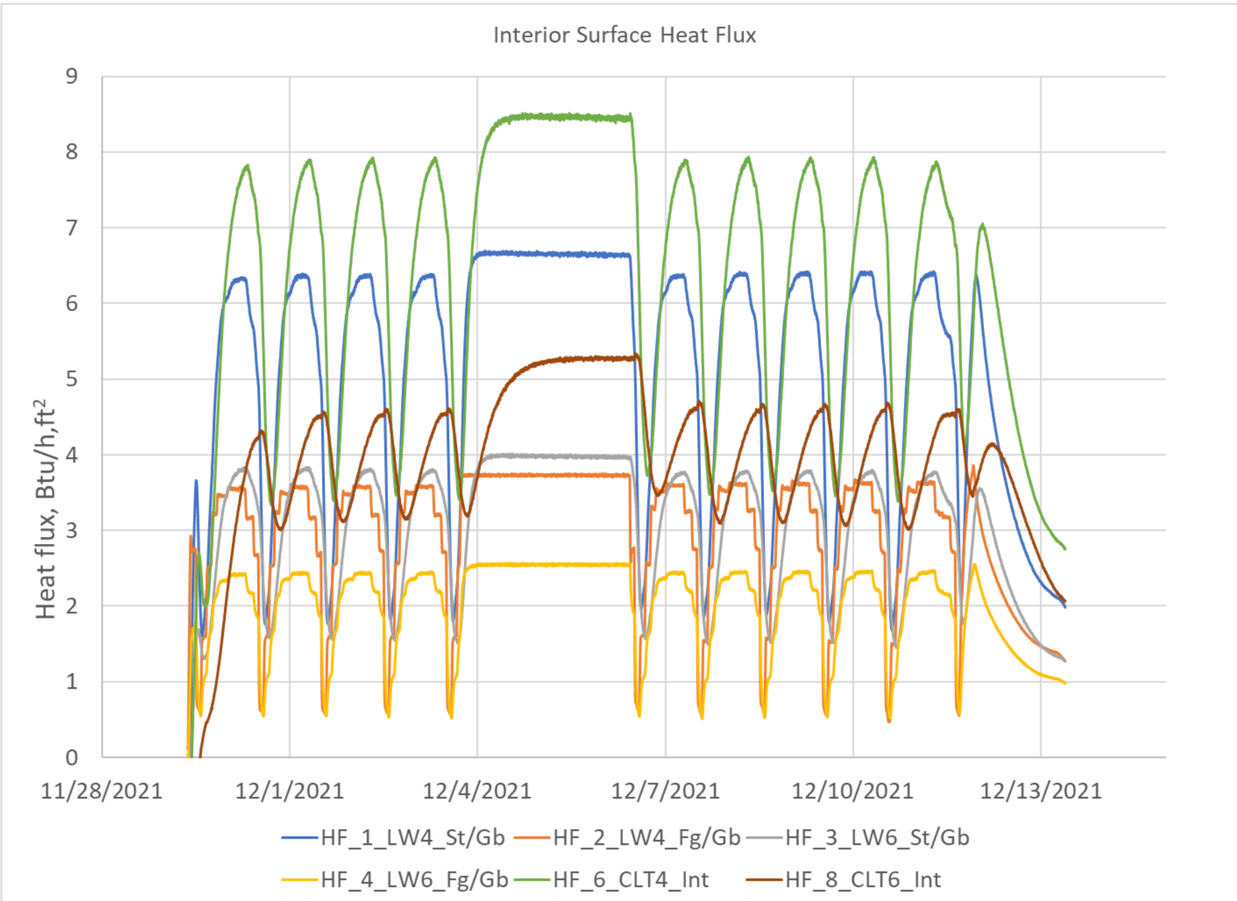

Figure 9. Heat fluxes on the interior side of the walls during testing in winter conditions.

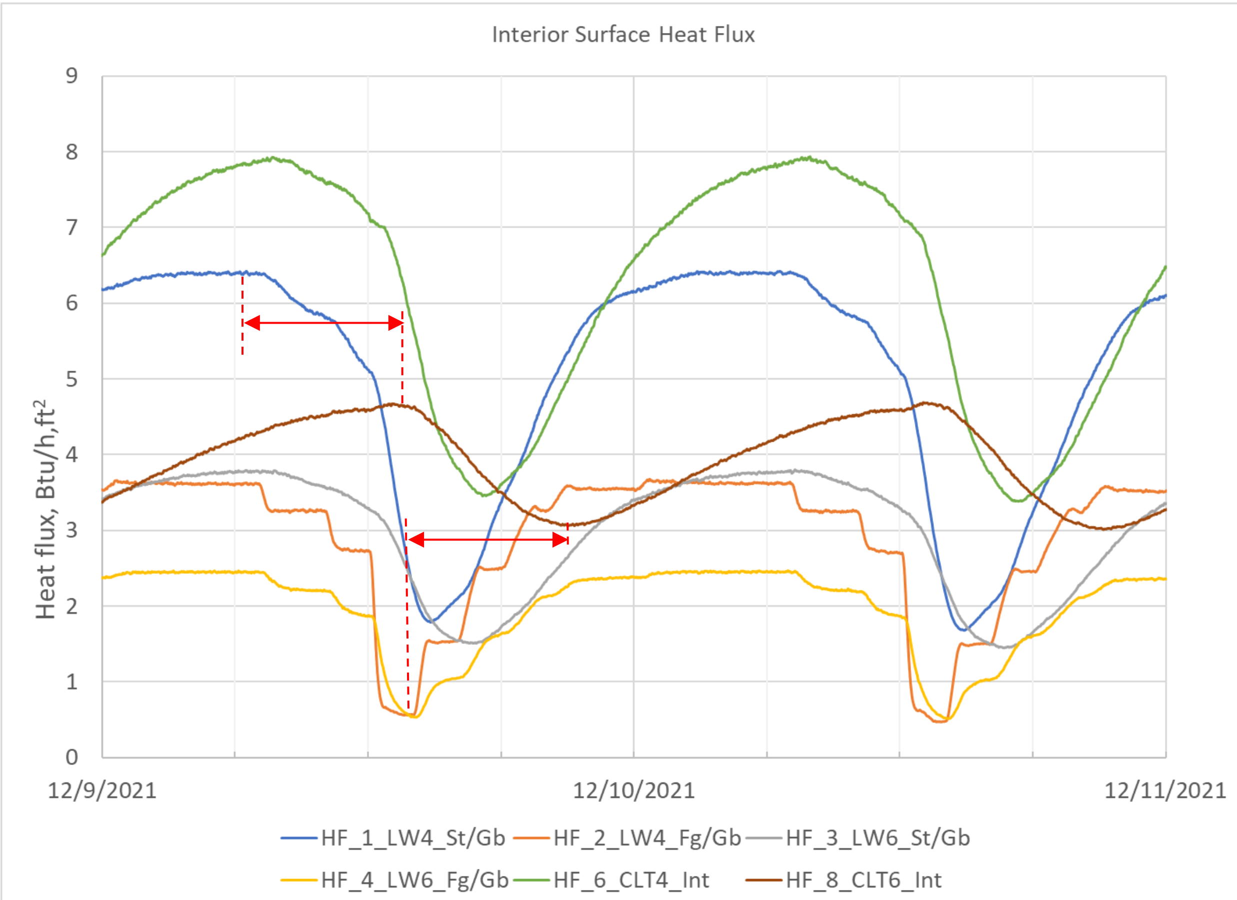

Figure 10. A close look at the interior heat fluxes during testing in winter conditions.

Figure 10 shows the seven-hour delay in the heat flux through the mass timber wall (CLT6). The highest heat loss of the mass timber wall (HF_8_CLT6) occurs at the same time as the lowest heat loss in the lightweight walls in the center of the cavity (HF_2_LW4_Fg/Gb and HF_4_LW6_Fg/Gb). The lightweight walls respond to the changes on the exterior surface with little time delay, whereas the thermal mass of the CLT structures delays the response. The stepwise heat flux in the center of the cavity in the lightweight walls is due to the stepwise control for the exterior surface temperature.

Figure 11 and Figure 12 show the surface temperatures of the assemblies on the indoor side as a function of time. The surface temperatures between the walls differ by 1.5°F during the night and 2°F during the day. At night, the lowest surface temperatures are experienced in the mass timber assemblies (CLT4 and CLT6) and at the stud locations in the lightweight assemblies (LW4_St/Gb and LW6_St/Gb). The center of the insulated cavity has the highest temperatures. The higher the insulation's R-value, the higher the surface temperature: the 2×6 wall (LW6_Fg/Gb, R-23) has a higher temperature than that of the 2×4 wall (LW4_Fg/Gb, R-13).

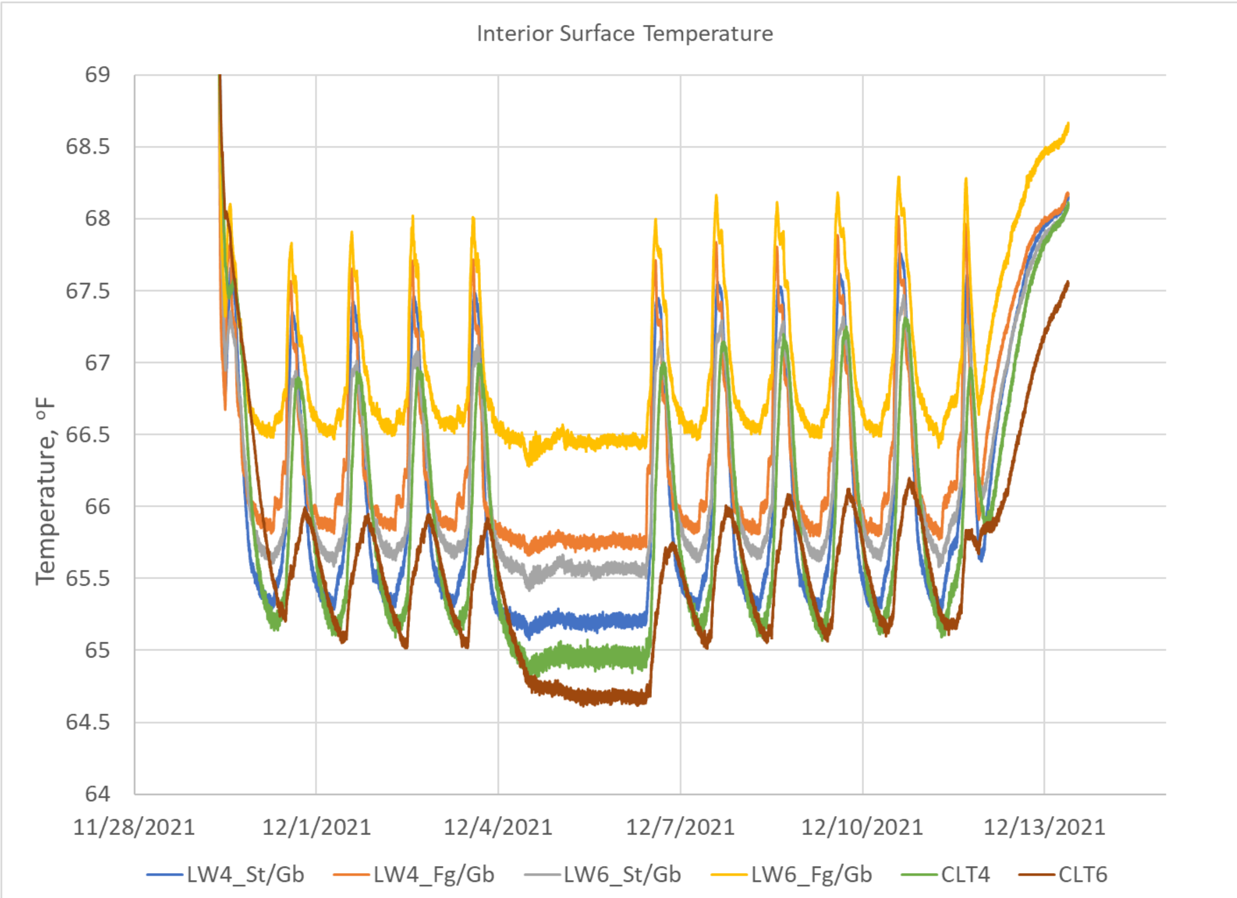

Figure 11. Surface temperature facing the indoor climate during testing in winter conditions.

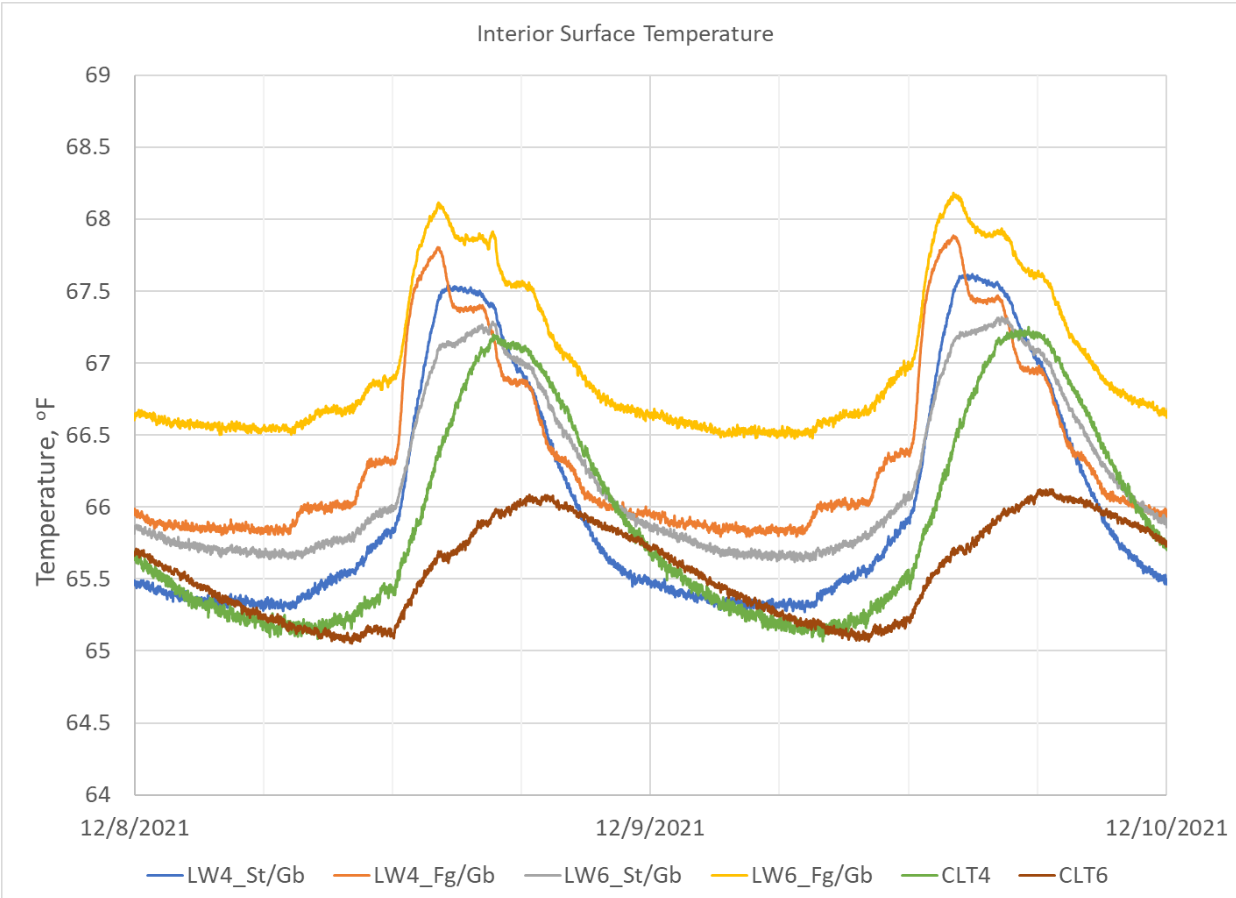

Figure 12. A closer look at the surface temperature facing the indoor climate during testing in winter conditions.

2.3.2 Test results in summer conditions

Figure 13 shows the air temperature in the exterior and interior climate chambers, as well as the exterior temperature of the 2×6 assembly during the testing under summer conditions. Note that the surface temperature sensor failed in the latter part of the test, and data during the last days are missing for it.

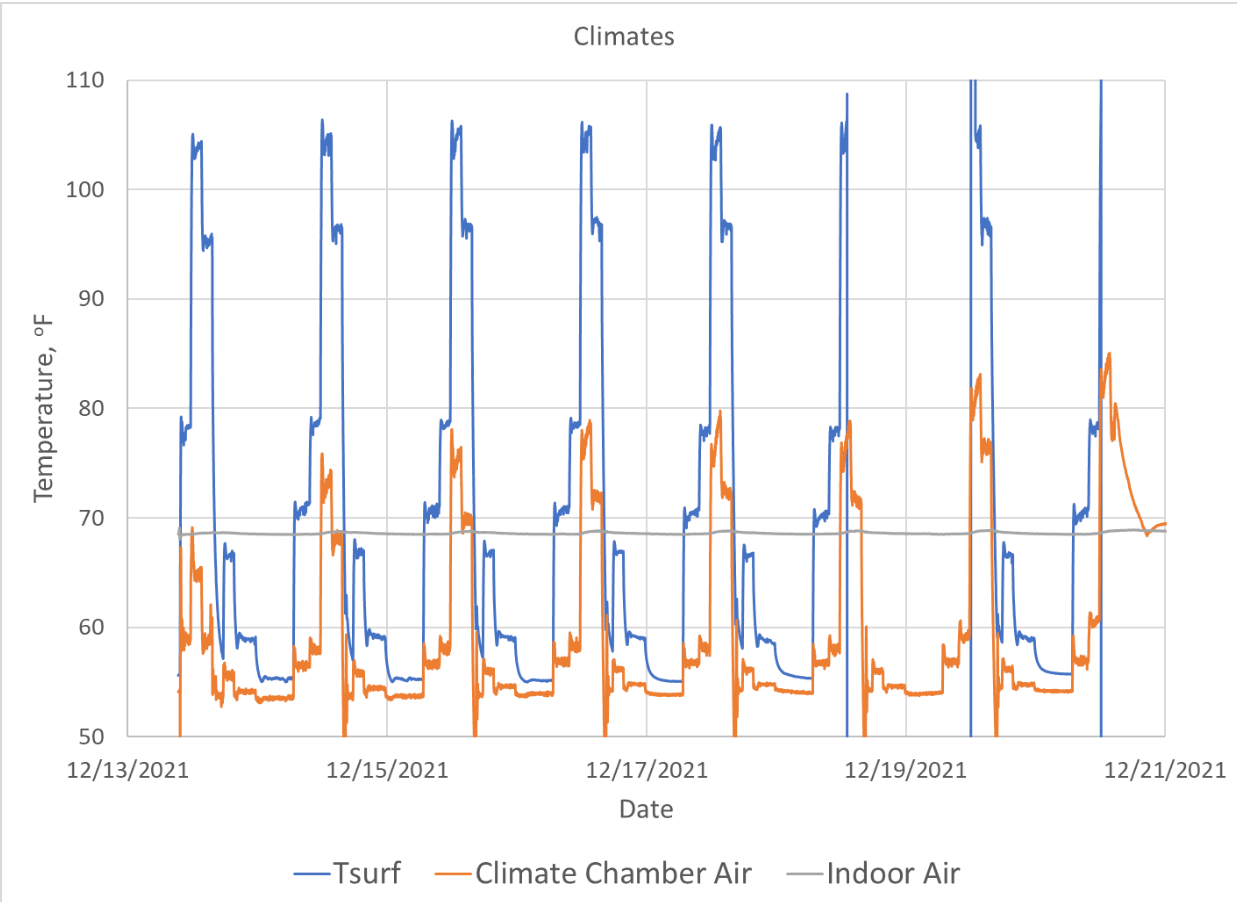

Figure 13. Air temperatures in climate and indoor chamber, and the exterior surface temperature during testing in summer conditions.

The heat fluxes on the interior surface during testing in summer conditions are shown in Figure 14 and Figure 15. The dip in heat flux in the middle of the day in the lightweight wall assemblies demonstrates how quickly the lightweight assemblies respond to the excitation on the exterior surface temperature. The mass wood assemblies show no significant change in the heat flux due to a short-lived temperature increase on the outer surface.

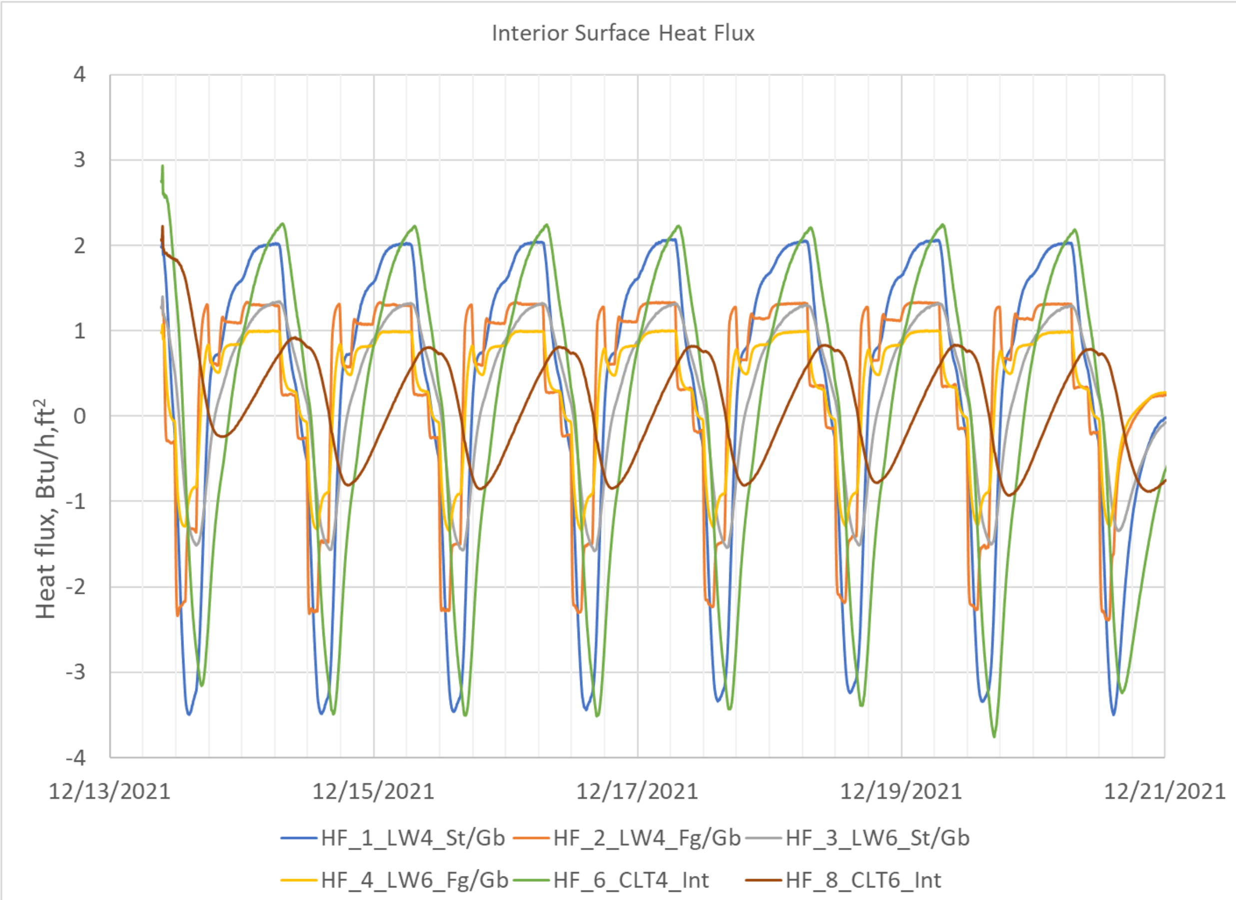

Figure 14. Heat fluxes on the interior side of the walls during testing in summer conditions.

A time delay of six hours in the heat flux through the 6 in. thick CLT wall (CLT6) is clearly visible in Figure 15. The heat loss peaks slightly earlier than the heat flux in the center of the cavity in the lightweight wall that is already at peak heat gain into the interior of the room. The peak heat gains and losses in the 6 ¾ in. CLT (HF_8_CLT6_Int) are less than half of those in the 4 in. CLT (HF_6_CLT4_Int). The thickness of the CLT and the thermal response are not linearly related. Mass wood has thermal mass, but it also insulates quite well at the same time. Therefore, increasing the thickness of the mass wood structure from 4 in. to 6 ¾ in. shows a significant difference in transient performance both in peak heat fluxes and time shift of the peak.

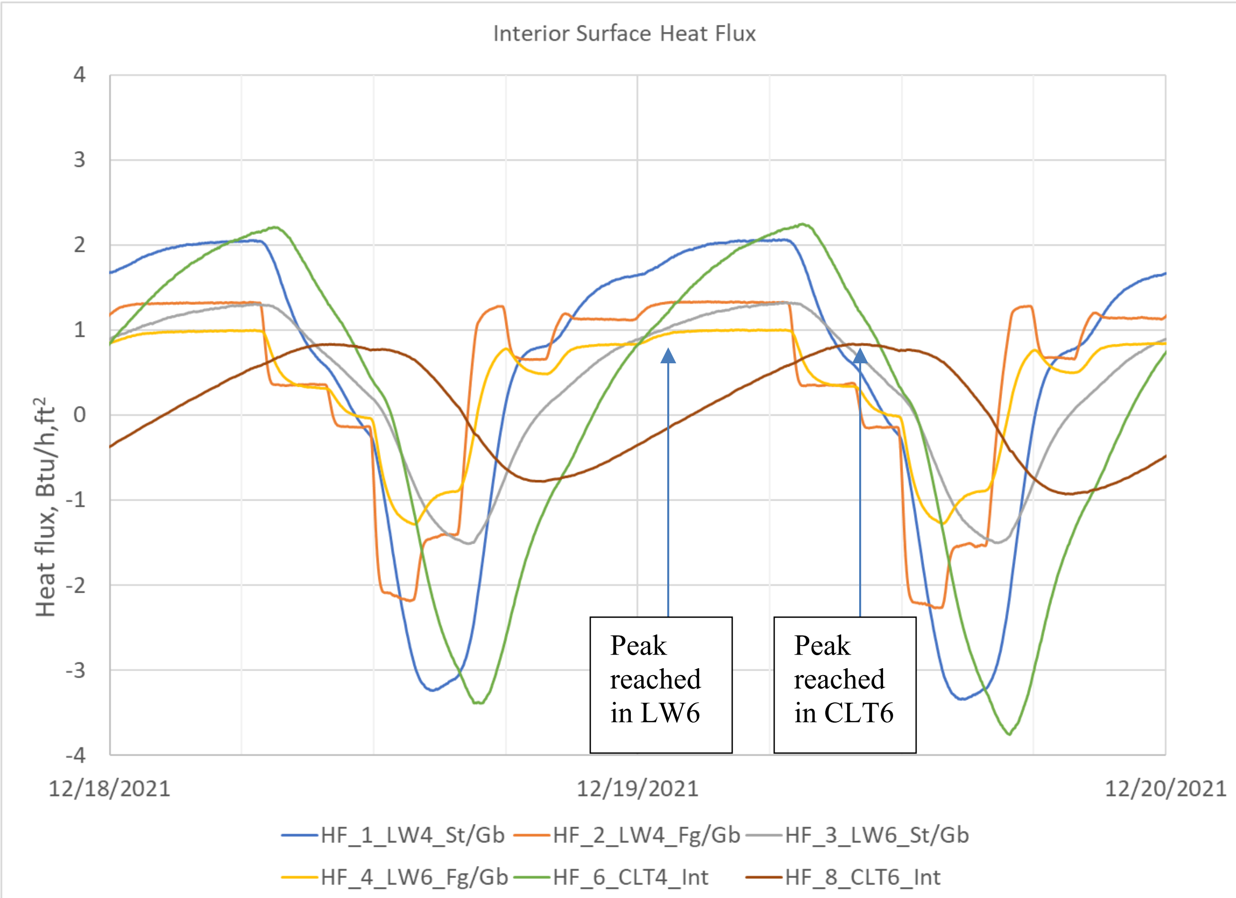

Figure 15. A close look at the interior heat fluxes during testing in summer conditions.

Figure 16 shows the interior surface temperatures on the walls during the summer test conditions. The dark brown line clearly shows the dampening effect of mass timber on how exterior weather conditions penetrate through the wall. The surface temperature fluctuation in the 6 in. CLT wall (CLT6) is within 1°F, whereas the lightweight walls experience 2–2.5°F fluctuation.

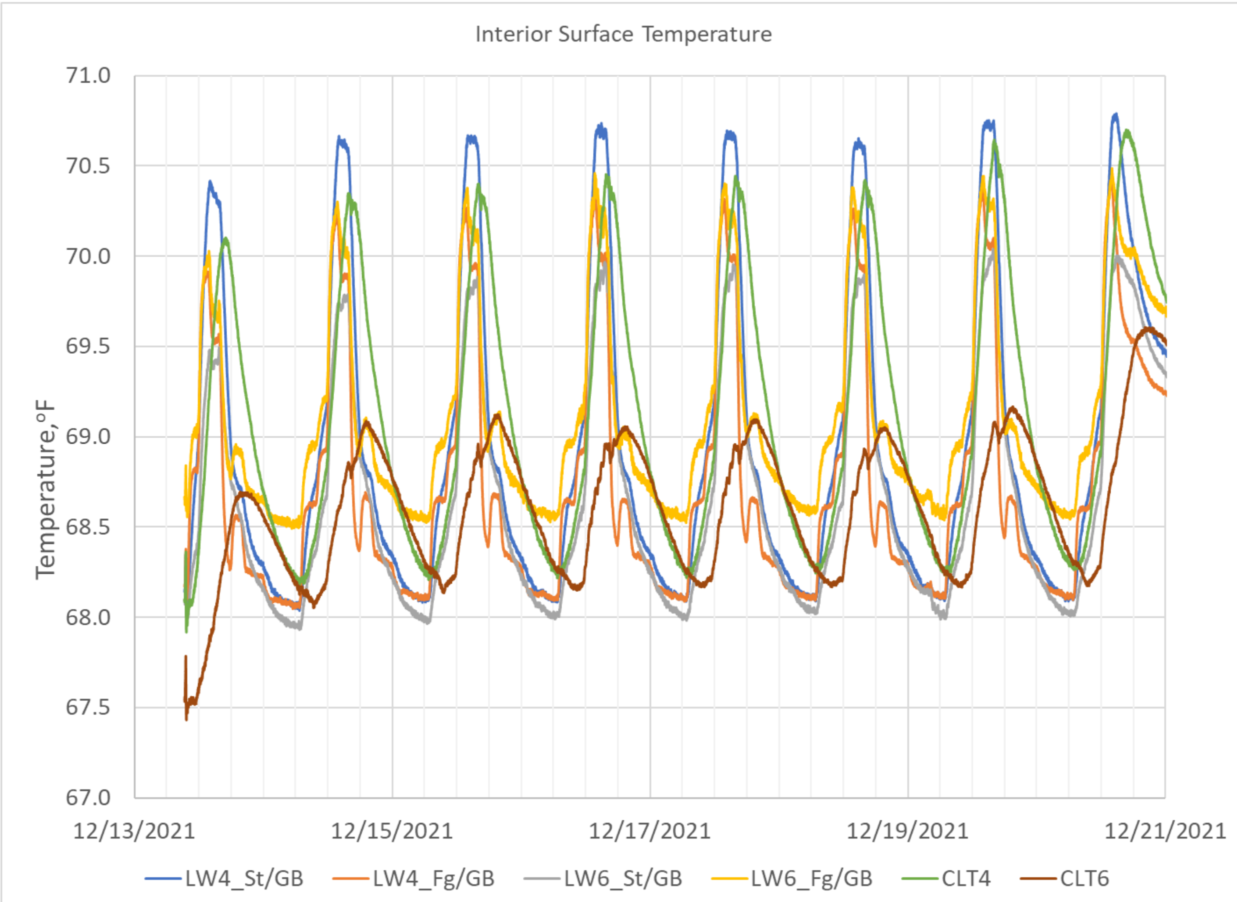

Figure 16. Surface temperature facing the indoor climate during testing in summer conditions.

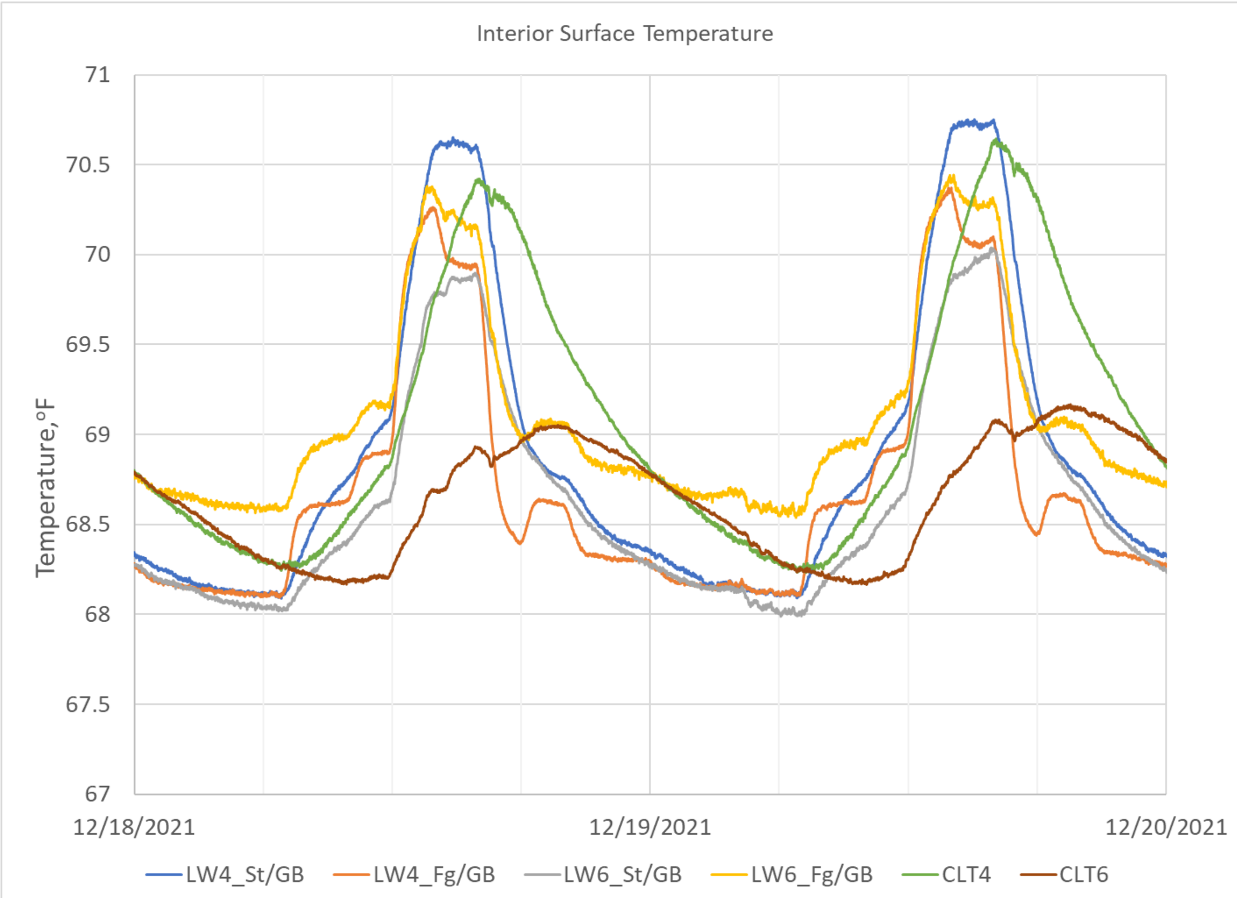

Figure 17. A closer look at the surface temperature facing the indoor climate during testing in summer conditions.

2.4 VALIDATING SIMULATION MODELS

The assemblies were simulated with the COMSOL Multiphysics software (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 both in the winter and summer conditions sequentially.

The simulation results show a good transient response with regard to thermal mass. However, the level of measured and simulated heat flux differed. The insulation materials were tested in a heat flow meter, and the measured thermal conductivity values were used in the simulations (R-13 batt: k = 0.039 W/mK (0.271 Btu-in/h,ft^2, °F), R-23 batt: k = 0.034 W/mK (0.236 Btu-in/h,ft^2, °F)). The heat flux transducers were also calibrated in the heat flux meter. The heat flux in the middle of the insulated cavity was measured to be higher both in the 2×4 wall and in the 2×6 wall than what was simulated with the known surface temperatures. In the 2×6 wall, the simulated heat flow was about 20% lower than that measured in steady state. The mass timber walls showed very similar behavior in the simulations and the measurements.

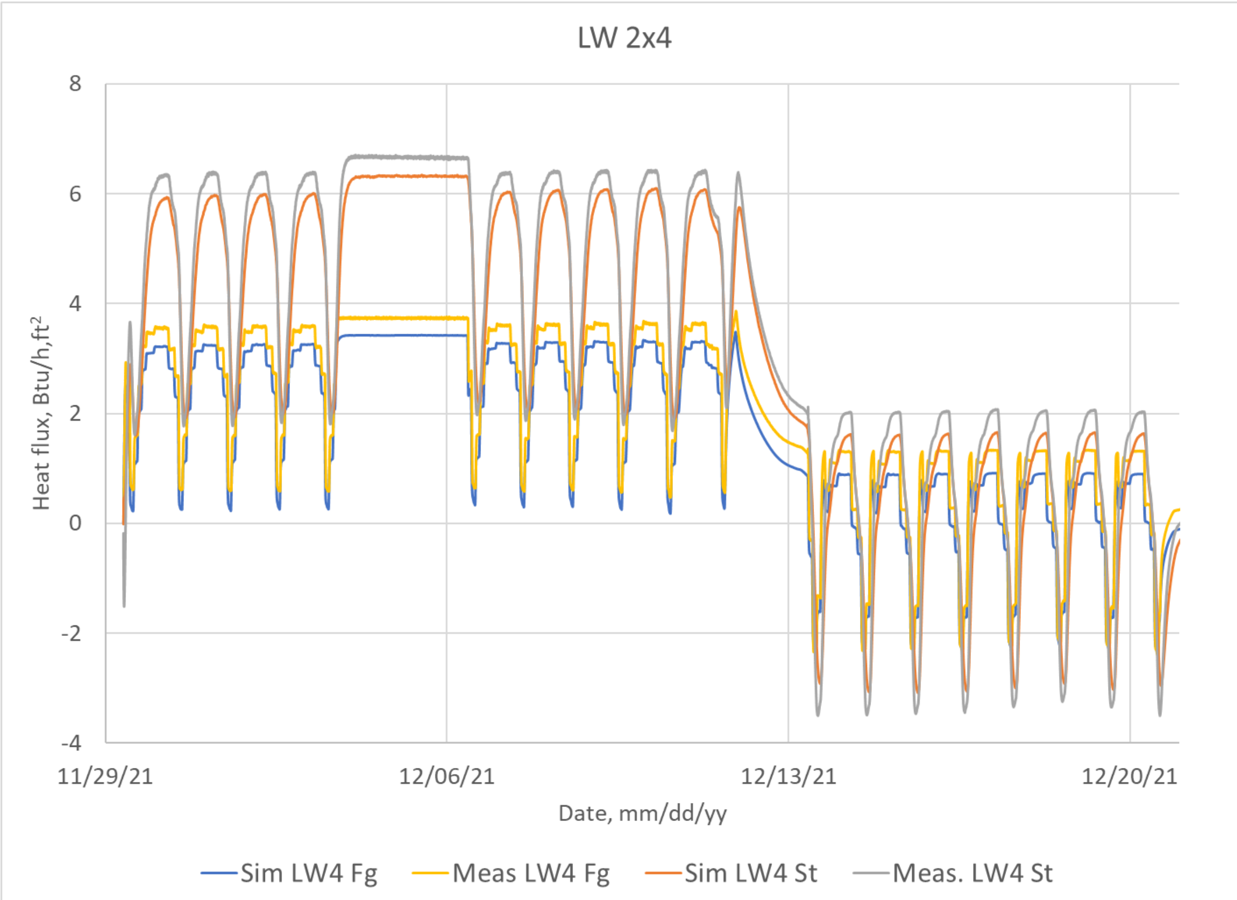

Figure 18. Heat flux through the interior wall surface in the 2×4 wall: simulated and measured values at the stud (St) and in the center of the cavity (Fg).

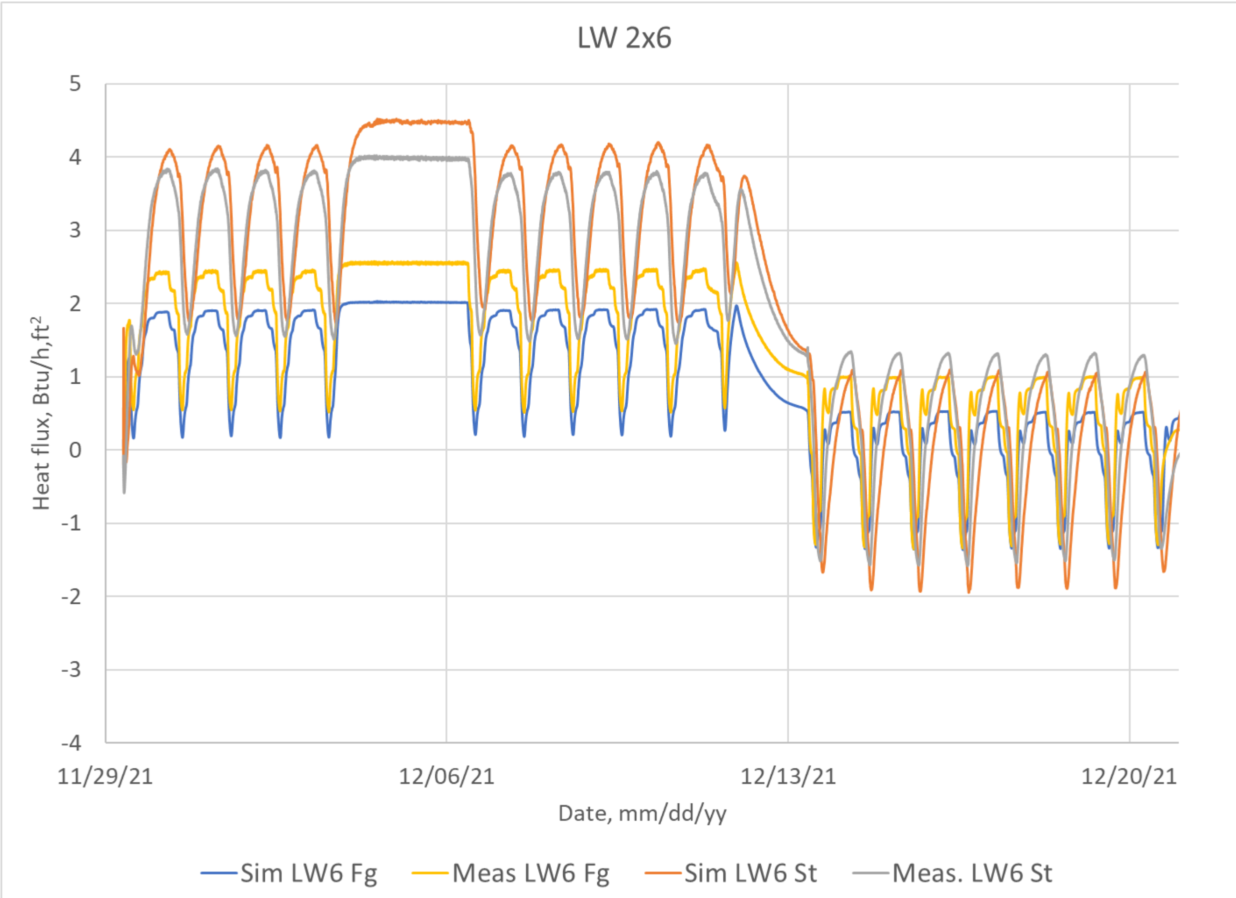

Figure 19. Heat flux through the interior wall surface in the 2x6 wall: Simulated and measured values at the stud (St) and in the center of the cavity (Fg).

The simulated and measured heat fluxes in the middle of the cavity in the 2×6 wall with R-23 insulation differ as much as 20%. This disagreement is due to the voltage output of the heat flux transducer becoming low and inaccurate when the heat flux becomes low. In the future, it is recommended to use heat flux transducers with higher sensitivity or multiple sensors in series to increase the voltage output. The calculated steady-state one-dimensional heat flux in the middle of the cavity on 12/05/21 using surface temperatures and the R-value of the insulation agreed with the simulations, giving the same value as measured (2 Btu/h,ft^2). Since the R-value of the insulation was measured in the heat flow meter apparatus, and the installation filled the cavity without gaps, it is likely that the heat flux transducer shows higher heat flux than the actual heat flux. When ignoring the difference in the heat flux level, the transient responses of the measured and simulated heat fluxes have the same trend and amplitude in time, indicating that the thermal mass is properly accounted for in the simulations.

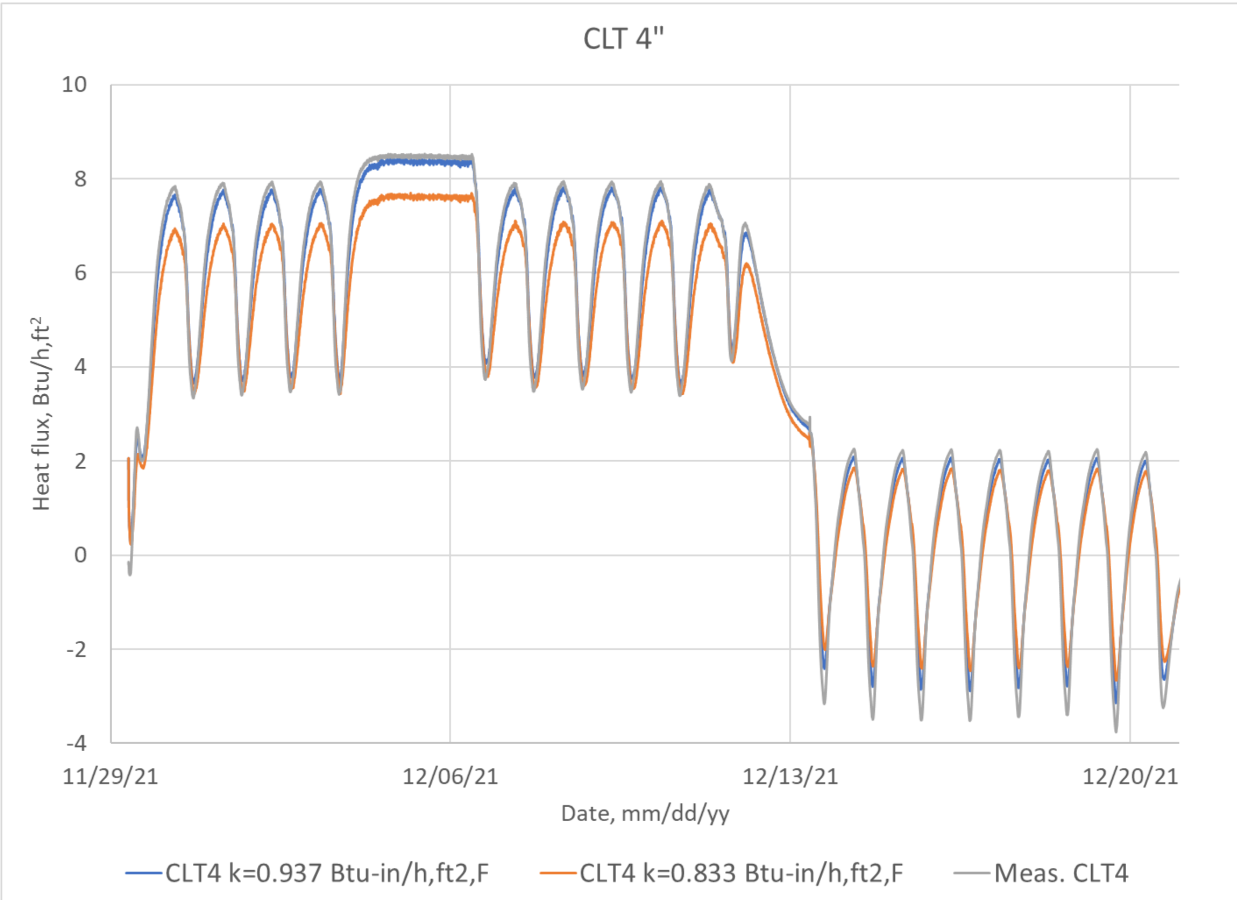

Figure 20. Heat flux through the interior wall surface in the 4 in. CLT wall: simulated and measured values. Simulated results were calculated with two thermal conductivities.

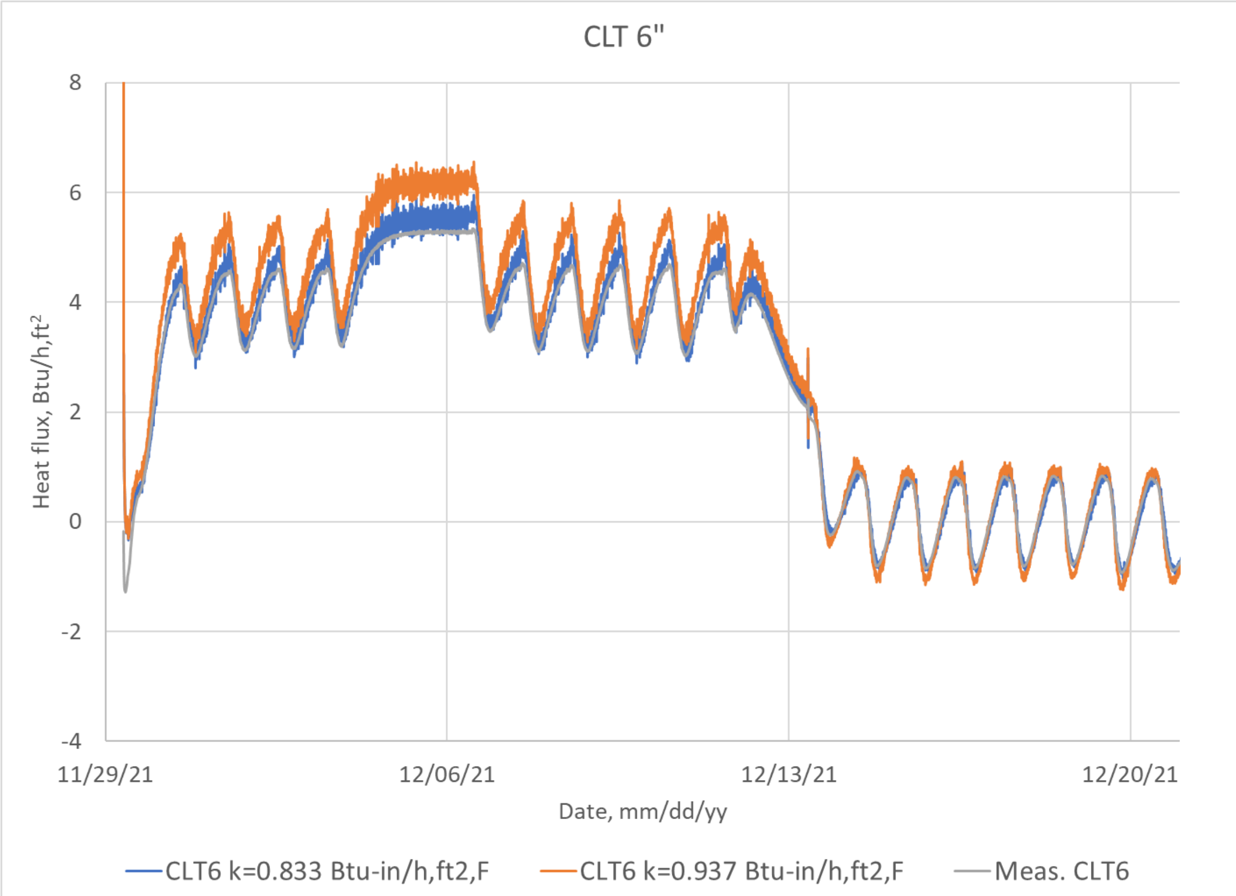

Figure 21. Heat flux through the interior wall surface in the 6 in. CLT wall: simulated and measured values. Simulated results were calculated with two thermal conductivities.

2.5 EFFECTIVE MATERIAL PROPERTIES OF LIGHTWEIGHT WALLS FOR ENERGYPLUS SIMULATIONS

EnergyPlus 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. Figure 22 shows the simulation setup used to evaluate the thermal bridge (area A1) in COMSOL and its impact on thermal performance.

The wall assemblies in the laboratory tests have wall cavities with one stud only. 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 taken into account in energy calculations by using a framing fraction (FF). The FF 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 2×4 walls (frame spacing 16 in. o.c.) and 20% for 2×6 walls (24 in. o.c.) (RESNET).

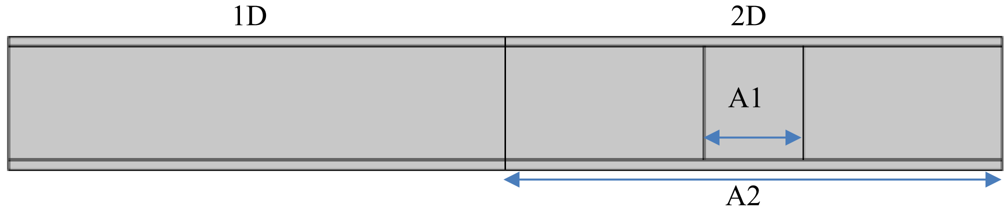

Figure 22. One-dimensional (1D) and two-dimensional (2D) structures for the evaluation of heat transfer side by side. The framing fraction (FF) is A1/A2.

The need is to create effective material properties for a material layer that replaces the insulation and the wood frame in the cavity. The materials in the simulated set were (material and thickness): OSB 7/16 in., R-13/R-20 Fiberglass 3.5 in. at 16 o.c./5.5 in. at 24 o.c., wood and gypsum board ½ in.
The material properties used in the calculations are listed in Table 2.

Table 2. Material properties used in the calculations to develop effective properties.

Material	Density, pcf	Heat capacity, Btu/lb,°F	Thermal conductivity, Btu-in/h, ft^2, °F
OSB	31	0.45	0.763
Fiberglass R-13 (2×4) R-20 (2×6)	 0.62 0.62	 0.20 0.20	 0.271 0.236
Wood	25	0.39	0.694
Gypsum board	39	0.21	1.110

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. Steady-state heat transfer calculations allowed adjusting the effective thermal conductivity for the 1D layer to match the heat flow of the 2D assembly. Finally, a dynamic test was carried out to compare the heat flux through the 1D and 2D walls. Figure 23 compares the heat flux through the interior surface of the 2D and the 1D 2×6 lightweight assemblies. The 1D assembly uses effective thermal properties. The transient response of the 2D wall cannot be fully replicated with a 1D setup, but the main trends are acceptable. Heat flux is shown through the interior surface of the wall when exposed to the same winter and summer conditions as in the testing of assemblies in the LSCS chamber. The last hours of the chamber conditions were modified to show the steady-state response. In steady state, the heat fluxes of the two walls match perfectly.

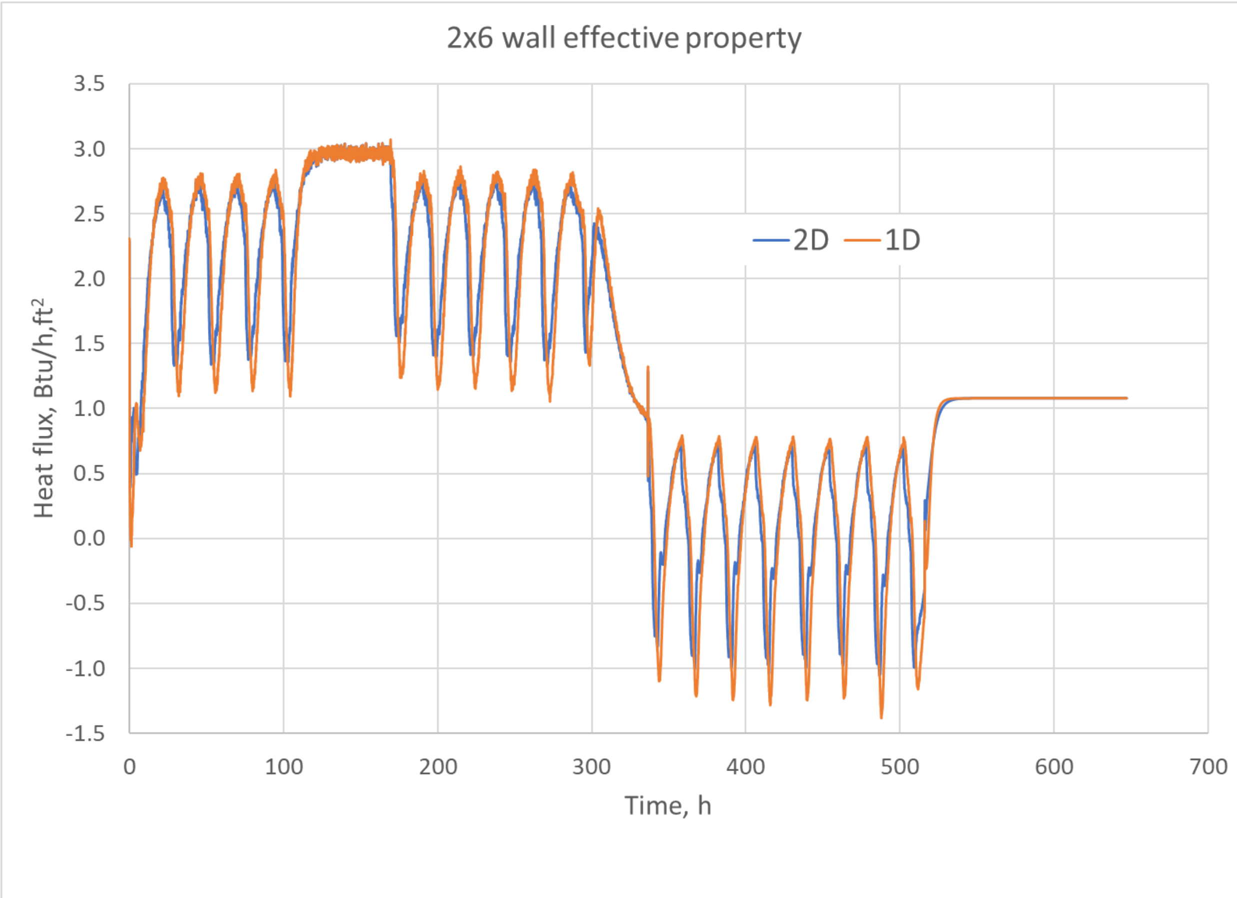

Figure 23. Dynamic testing of the effective thermal properties of the cavity insulation layer in the 2×6 wall.

3. IMPACT OF MASS WOOD ON PEAK DEMAND AND ENERGY USE

The simulations of the laboratory tests confirmed that the simulation model and model parameters in dynamic conditions are representative of the actual thermal performance of the lightweight and mass wood wall assemblies. The multidimensional lightweight wall assembly was further developed to a 1D representation with the same thermal performance to use the assembly in EnergyPlus.

The whole-building simulation model EnergyPlus™ v9.6 (DOE 2021a) was used to evaluate the impact of mass timber wall assemblies on the energy use, peak demand, and thermal comfort on the DOE prototype building (DOE 2021b). The DOE prototype building, following the IECC 2021 energy code (Figure 24), used in the simulations is a two-story, single-family building on a slab. A heat pump provides heating and cooling. The conditioned window-to-wall ratio is 15%. The conditioned area is 2,377 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, these simulations are thermal only: the moisture effects of wooden structures were not taken into consideration.

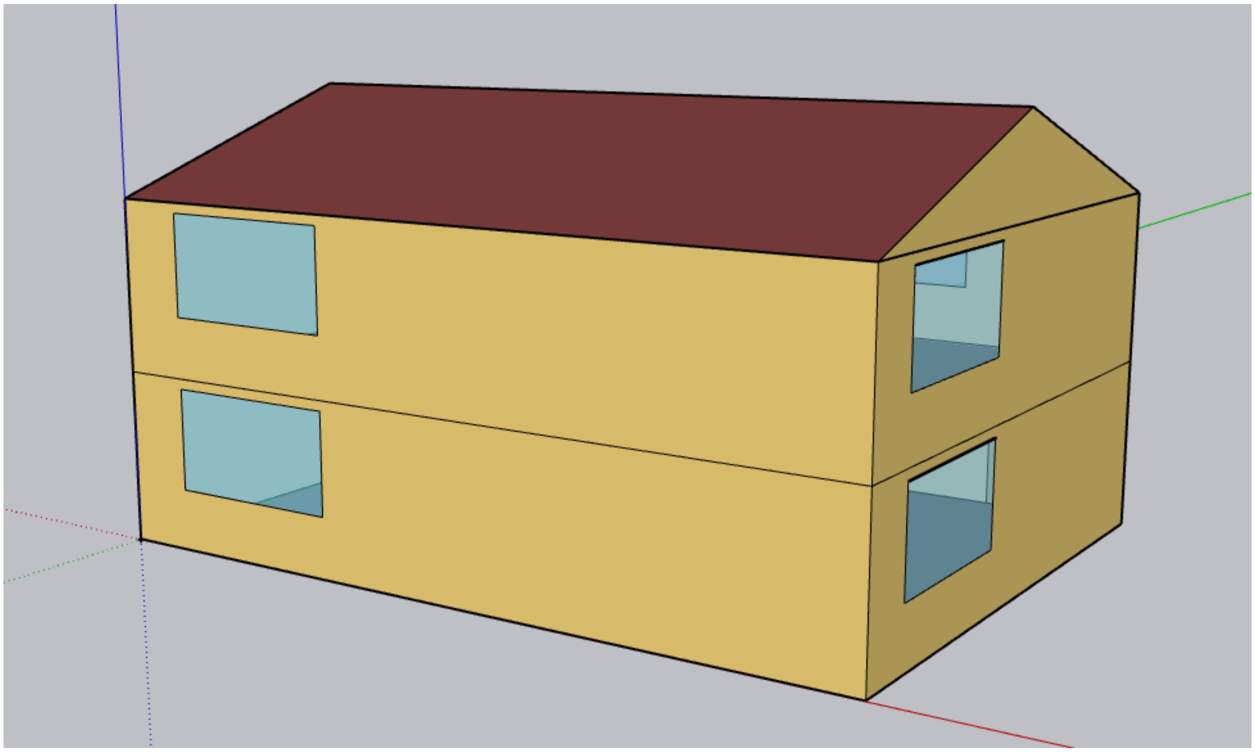

Figure 24. DOE Residential Prototype building used in simulations.

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 was used as the baseline, with the exterior wall assemblies slightly modified to meet the International Residential Code (IRC) 2021 requirements for lightweight wood frame and mass timber walls.

The IRC 2021 building code for the building envelope has two paths: U-factor requirements and the R-value alternative (Table 3).

Table 3. IRC 2021 building envelope requirements.

	U-factor		R-value alternative	
Climate zone	Wood frame	Mass wall*	Wood frame	Mass wall**
2A	0.084	0.165	R-13	R-4/R-6
3B	0.060	0.098	R-20 or R-13+5	R-8/R-13
5B	0.045	0.082	R-20+5 or R-13+10	R-13/R-17

* The code states that mass timber is considered a mass wall. Additionally, any wall having a heat capacity greater than or equal to 6 Btu/ft^2,°F is also considered a mass wall.
**For example, R-4/R-6: first value (4) applies when more than 50% of insulation is on the exterior side of the wall; 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. Material layers, effective R-values (h,ft^2,°F/Btu), and resulting U-factors for baseline and solid mass timber walls.

Climate Zone (CZ) Wall / Layer	2A Wood frame (Base, LW)	2A Mass timber (MT)	3B Wood frame (Base, LW)	3B Mass timber (MT)	5B Wood frame (Base, LW)	5B Mass timber (MT)
Exterior surface film coefficient	**R-0.17**	**R-0.17**	**R-0.17**	**R-0.17**	**R-0.17**	**R-0.17**
Cladding (synthetic stucco or similar) d=1/8 in. k=0.6 Btu-in/h,ft^2, °F ρ=25 pcf c_p=0.21 Btu/lb,ºF	**R-0.2**	**R-0.2**	**R-0.2**	**R-0.2**	**R-0.2**	**R-0.2**
Cementitious sheathing	d=0.5 in. k=0.65 Btu-in/h,ft^2, °F ρ= 42.8 pcf **R-0.767**					
Continuous insulation d=see CZ k=0.2 Btu-in/h,ft^2, °F ρ=1.3 pcf c_p=0.35 Btu/lb, °F			d=1" **R-5**		d=2" **R-10**	
OSB d=7/16” k=0.8 Btu-in/h,ft^2, °F ρ=34 pcf c_p=0.29 Btu/lb, °F	**R-0.54**		**R-0.54**		**R-0.54**	
Fiberglass insulation/Stud d= see CZ k= see CZ ρ= see CZ c_p=0.20 Btu/lb,ºF	FF*=23% d=3.5 in. k=0.38 Btu-in/h,ft^2, °F ρ= 15.5 pcf **R-9.18**	N/A	FF*=23% d=3.5 in. k=0.38 Btu-in/h,ft^2, °F ρ= 15.5 pcf **R-9.18**	N/A	FF*=23% d=3.5 in. k=0.38 Btu-in/h,ft^2, °F ρ= 15.5 pcf **R-9.18**	N/A
Mass timber Thickness d=see CZ k=0.83 Btu-in/h,ft^2, ºF		d=6 in.		d=7.8 in.		d=9.45 in.
Drywall d=1/2 in. k=0.6 Btu-in/h,ft^2, °F ρ=50 pcf c_p=0.26 Btu/lb, °F	**R-0.45**		**R-0.45**		**R-0.45**	
Interior surface film coefficient	**R-0.68**	**R-0.68**	**R-0.68**	**R-0.68**	**R-0.68**	**R-0.68**
Total R-value, h,ft^2, °F/Btu	*R-11.99*	*R-8.26*	*R-16.22*	*R-10.42*	*R-21.22*	*R-12.41*
U-value, Btu/h,ft^2, °F	0.083	0.121	0.062**	0.096	0.047**	0.081
IRC 2021 U-value req.	0.084	0.165	0.060	0.098	0.045	0.082

*Framing fraction

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

Additionally, the second series of mass timber walls were simulated in all three climate zones using a constant thickness 6" of mass timber, with exterior continuous insulation (CI) (Table 5) to bring the mass timber walls to the same U-value as the lightweight walls.

Table 5. Mass timber walls with exterior continuous insulation.

Climate zone (wall)/ Material layers	CZ 2A (MT-wCI)	CZ 3B (MT-wCI)	CZ 5B (MT-wCI)
Cladding (synthetic stucco or similar)	Yes	Yes	Yes
Mineral fiber continuous insulation d=see CZ k=0.23 Btu-in/h,ft^2, °F ρ=6 pcf c_p=0.2 Btu/lb, °F	d=1 in. R-4.3	d=2 in. R-8.6	d=3 in. R-12.9
R-value, h,ft^2, °F/Btu	R-12.56	R-16.86	R-21.16
U-value, Btu/h,ft^2, °F	0.080	0.059	0.047

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

3.1 ANNUAL ENERGY CONSUMPTION

Figure 25 shows the simulated annual heating and cooling energy consumption. Figure 26 has the same data separating the heating, cooling, and fan energy use relative to the base case. 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. Similar performance occurs in climate zone 2 (Houston, TX). 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% that of the baseline case (heating in mass timber building was 1% lower, resulting in equal total energy use).

Solid mass timber wall (MT) had the following performance as compared to the baseline:

- Houston, TX: 1% lower heating, 1% higher cooling, and equal total energy use
- Los Angeles, CA: 9% lower heating, 22% lower cooling demand, and 15% lower total energy use
- Golden, CO: 17% higher heating, 12% lower cooling, and 12% higher total energy use

Mass timber wall with continuous insulation (MT-wCI) had the following performance as compared to the baseline:

- Houston, TX: 11% lower heating, 6% lower cooling, and 8% lower total energy use
- Los Angeles, CA: 23% lower heating, 18% lower cooling demand, and 19% lower total energy use
- Golden, CO: equal heating, 11% lower cooling, and 2% lower total energy use

Extreme insulation case with R-100 (R-100) continuous insulation resulted in the following performance as compared to the baseline:

- Houston, TX: 26% lower heating, 16% lower cooling, 20% lower total energy use

- Los Angeles, CA: 41% lower heating, 6% lower cooling, 19% lower total energy use
- Golden, CO: 18% lower heating, 2% lower cooling, 16% lower total energy use

The results are summarized in Table 6.

Table 6. Annual energy savings compared to the lightweight walls

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

The above results show that the overall performance of mass timber walls with the current code-required insulation levels can be as effective as thermally light walls with extreme insulation levels. The total heating and cooling energy savings were the same for the mass timber walls with exterior continuous insulation (MT-wCI T) and for the R-100 walls (R-100 T) in Los Angeles, CA. In more extreme climates, such as the hot climate of Houston, TX, and the cold climate of Golden, CO, the savings are lower due to longer steady hot or cold weather periods during which the thermal mass effects cannot balance the heat gains and losses as effectively as in milder climates.

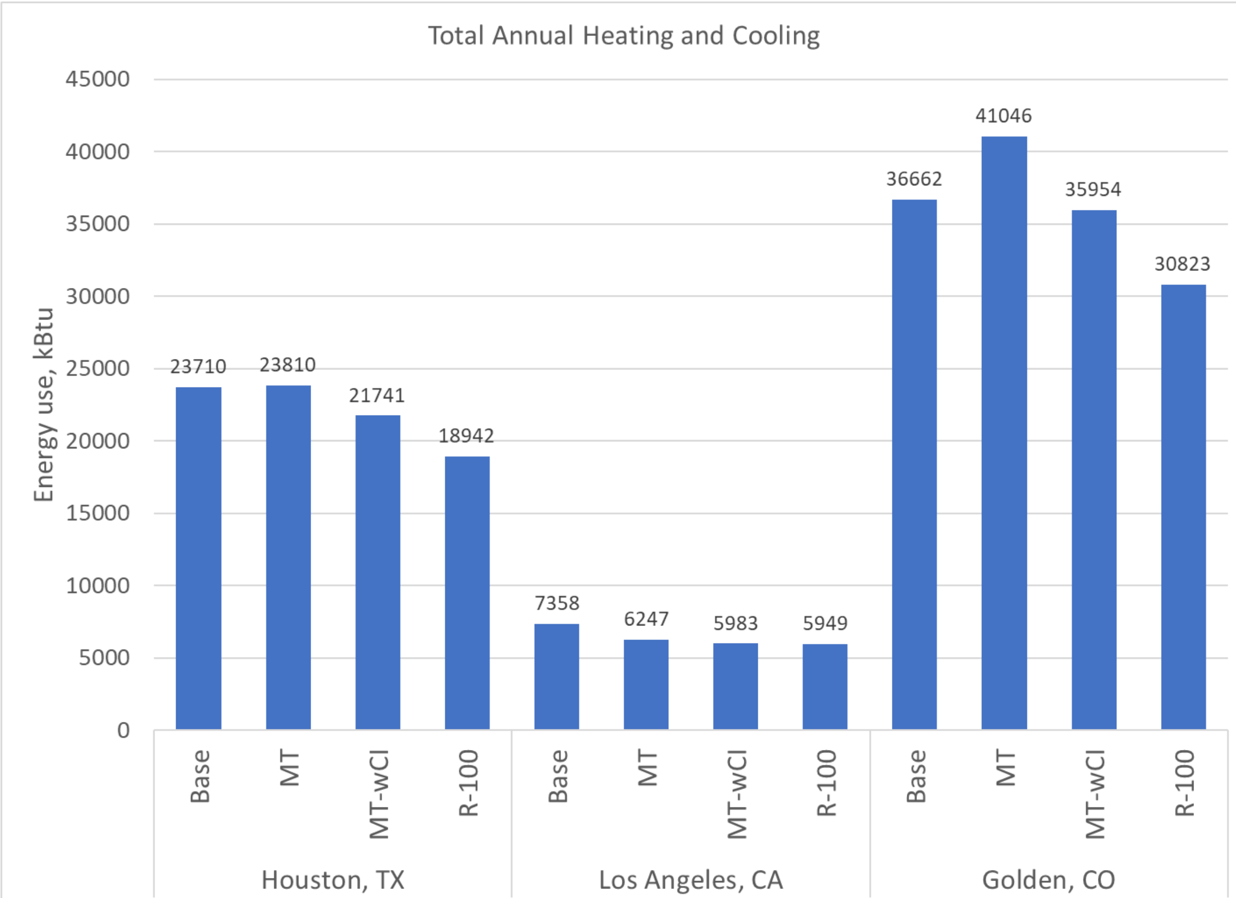

Figure 25. Total annual heating and cooling energy consumption (kBtu).

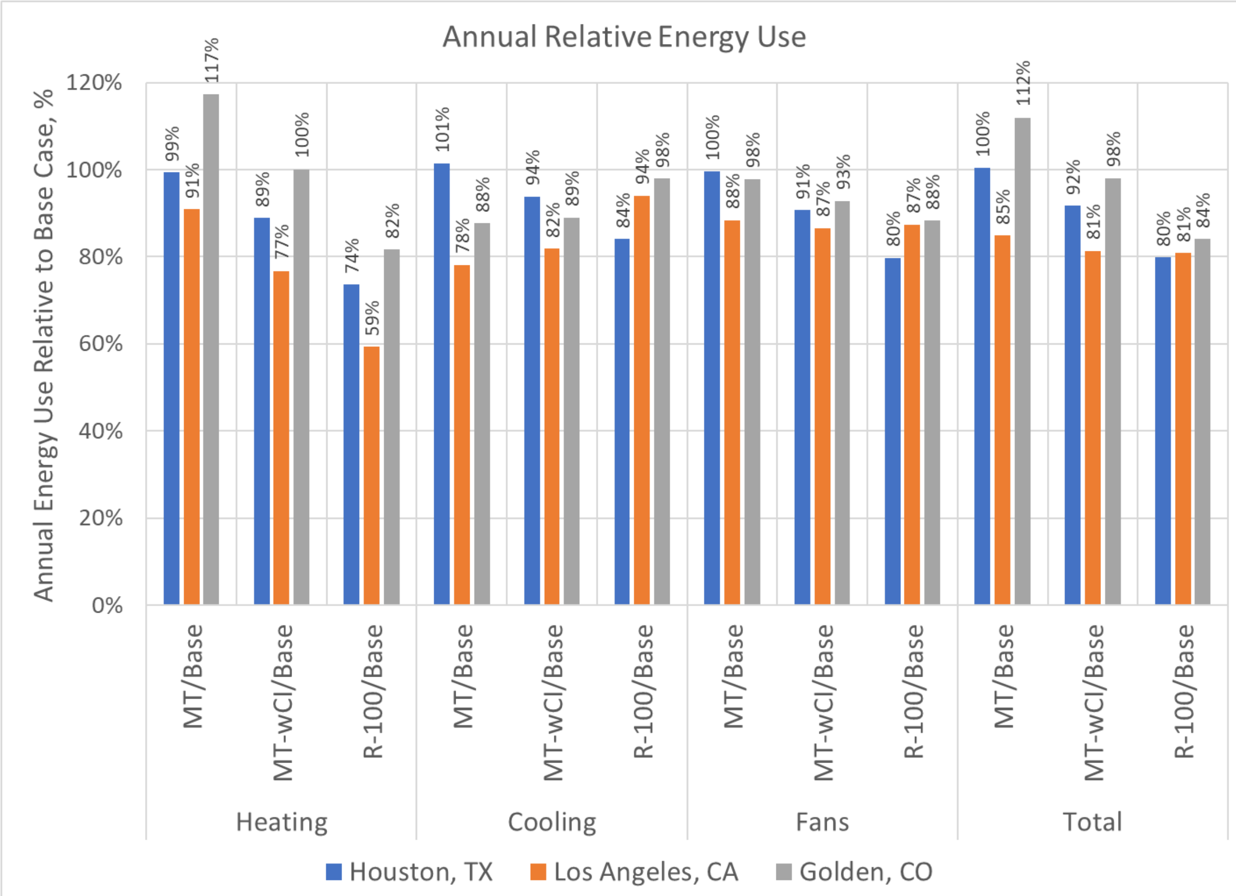

Figure 26. Relative annual heating and cooling energy use.

3.2 PEAK DEMAND AND MASS TIMBER

The peak demand was evaluated by analyzing the typical hourly heating, cooling demand, and heat flows through walls in 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 typical peak hours would reduce the energy costs and help the grid balance the energy demand and supply.

3.2.1 Hourly profiles of heating and cooling demand

Figure 27 shows the heating demand in Los Angeles, CA. LW means the lightweight baseline wall, MT is the solid mass timber wall and MT-wCI is the 6 in. mass timber wall with continuous insulation. The number, in the end, is the month indicator. The buildings with mass timber walls show significantly lower heating demand than those with lightweight walls. For example, in December, the mass timber wall (MT12) had about 30% lower peak demand, and the mass timber wall with continuous insulation (MT-wCI) had about 80% lower peak demand. In January, the mass timber walls had 30–40% lower heating demand, and the trend continues through the spring.

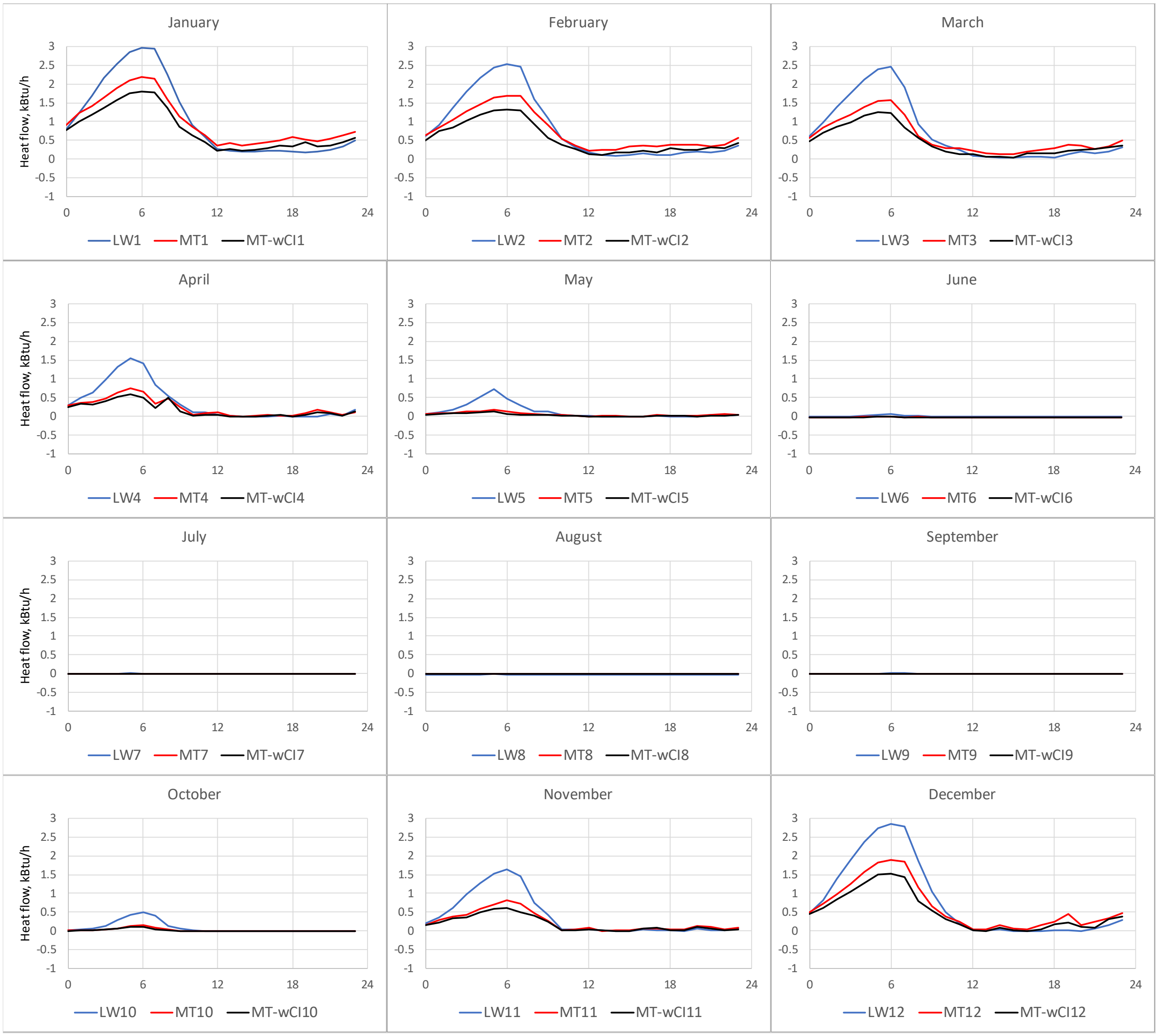

Figure 27. Typical hourly heating demand in Los Angeles, CA, in all the months of the year.

Figure 28 shows the cooling demand in Los Angeles, CA. During the months with the highest cooling demand—June to September—the two mass timber wall structures behaved very similarly, with only minor differences. The peak values for cooling with mass timber are 23–31% lower than in the baseline wall at the peak demand hour (5 pm). The cooling demand shifted to earlier hours with mass timber walls away from the peak demand time. A possible reason for the small differences in cooling demand between the solid mass timber wall (MT) and the exterior insulated mass timber wall (MT-wCI) is that the dampening of heat flows is largely caused by the interaction of the mass wood layer exposed to the indoor climate. In the case of heating demand (Figure 27), the mass timber is likely interacting more with the exterior climate and dampening the heat fluxes through the wall.

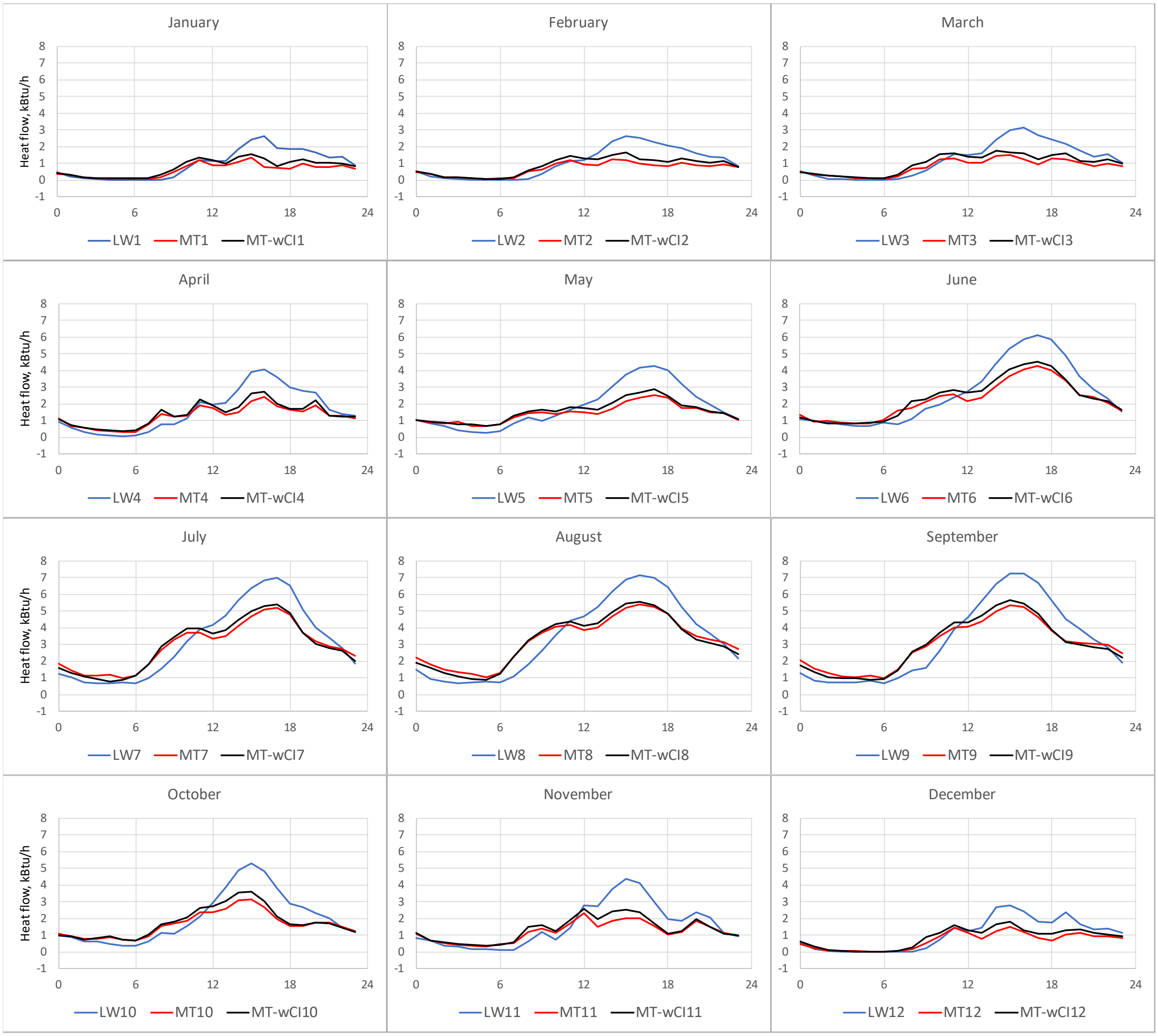

Figure 28. Typical hourly cooling demand in Los Angeles, CA, in all the months of the year.

3.2.2 Hourly profiles of heat fluxes through walls

The heat fluxes between the walls and the indoor climate depend not only on the thermal conductance of the walls but also on their thermal capacity. As seen in the laboratory test results, mass timber provides a several-hour time shift in the peak heat flow through the wall when the exterior conditions peak.
Figure 29 summarizes heat flows through all the walls in a typical day in all 12 months in Los Angeles, CA. The heat flows through the walls to the building are 38–50% lower in the mass timber walls than in the lightweight baseline walls during the peak hour at 5 pm. Again, a strong shift of heat flows away from the peak hours is prevalent.

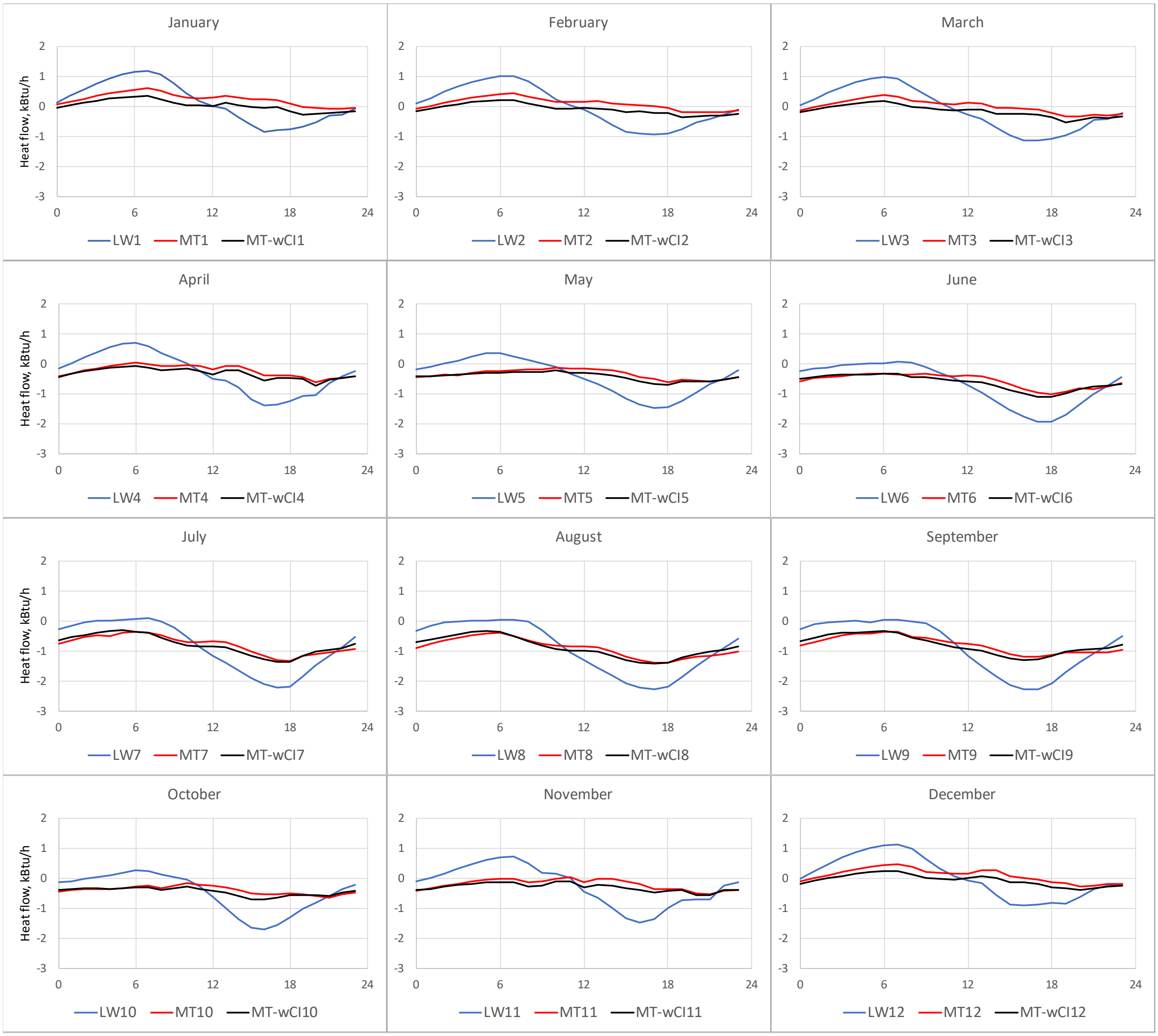

Figure 29. Typical hourly heat flows through all the walls in Los Angeles, CA, in all the months of the year.

4. IMPACT OF MASS WOOD ON THERMAL COMFORT

Thermal comfort is the goal for the occupants in the buildings. However, the typical thermal control in buildings is to maintain the indoor air temperature within a given range. The main factors that influence thermal comfort are those that determine heat gain and loss—namely, metabolic rate, clothing insulation, air temperature, mean radiant temperature, airspeed, and relative humidity. Additionally, psychological parameters, such as individual expectations, also affect thermal comfort. This project analyzed thermal comfort only briefly using the whole-building simulation tool with typical temperature controls for heating and cooling. Instead of fixing the indoor air temperature, controlling for thermal comfort can provide energy savings and better thermal comfort for occupants. An upcoming project will further assess the thermal comfort in lightweight and mass timber buildings with different control scenarios to address the knowledge gaps such as how building envelope and heating and cooling systems impact thermal comfort.

The DOE prototype building has only one zone; that is, 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.

In Table 7, "time not comfortable based on simple ASHRAE 55-2004" shows how many hours the space is not comfortable for each zone under the criteria of assuming winter clothes, summer clothes, or both summer and winter clothes. "Time Setpoint is Not Met" shows how many hours the space is more than 0.2°C 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 acceptability limit ASHRAE Std. 55 90% 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.

Table 7. Hours when comfort conditions were not met.

		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% Acceptability Limits [Hours]	Base	420	46	195
	MT	103	0	139
	MT-wCI	72	0	159

5. SUBJECT INVENTIONS, COMMERCIALIZATION POSSIBILITIES, AND PLANS FOR FUTURE COLLABORATION

The project did not create inventions but created new knowledge about the efficient use of mass timber structures to improve the energy performance of buildings. This study 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. This 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.

6. CONCLUSIONS

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 ORNL's to validate modeling against 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—especially on the peak demand as compared to the standard 2×4 and 2×6 lightweight wall systems. In this study, the annual energy savings with mass timber walls as compared to the baseline lightweight walls depending on the climate zones were up to 22%. The exception was the solid mass wall with a 72% higher U-value than the baseline wall, which had 12% higher heating and cooling energy use in Golden, CO. In addition, the lightweight walls with extreme insulation level (R-100 continuous insulation) saved less cooling energy as the mass timber walls. The results show that when the focus is on lowering the cooling energy use, more insulation is not necessarily the solution but instead adding thermal mass. Adding thermal mass is most effective in climates that have large variations in diurnal temperatures, which is when the thermal mass can actively participate in balancing heat flows. In environments such as cold climates with long winters, the thermal benefits are less pronounced. Thermal mass can provide shelter from extreme temperatures during power outages by maintaining the indoor temperatures in the buildings. However, this aspect of thermal mass was not part of this study.

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 improved thermal comfort by reducing the uncomfortable hours by up to 46%.

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