Influence of Building Design on Energy Benefit of Thermal Mass Compared to Prescriptive U-Factors

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ABSTRACT

The building industry is continually moving toward higher insulation levels and continuous insulation. Many building codes and standards recognize that thermally massive buildings need less insulation because they can store and gradually release heat compared to lightweight metal or wood-framed buildings. This relative reduction in required minimum insulation values for a massive building compared to a lightweight building varies by climate, but in general, ASHRAE Standard 90.1 allows about a 30% reduction in insulation levels. California's energy code allows up to an 86% reduction in insulation levels for "mass heavy" walls in certain climate zones.

However, most state building codes and energy standards do not currently reflect whether the thermal mass is located on the interior or exterior side of the insulation in the wall system. Also, the building type, geometry, window-to-wall ratio, and internal loads are not considered with respect to thermal mass in the prescriptive tables of ASHRAE 90.1 and various state energy codes. Our paper discusses the results of a series of whole-building energy simulations that we completed using the EnergyPlus computer program to study the effect of thermal mass relative to these parameters.

Our results show that the increased U-factors in the prescriptive tables in ASHRAE 90.1 and various state energy codes are justified in terms of accounting for the benefit of thermal mass. However, in all cases, having insulation on the exterior side of the thermal mass outperforms cases where the thermal mass is on the exterior side of the insulation. We show the most important parameters to maximize the benefit of thermal mass with regards to energy efficiency and demonstrate how the prescriptive tables in ASHRAE 90.1 and most state energy codes do not currently account for these benefits or parameters.

INTRODUCTION

The prescriptive U-factor tables in ASHRAE 90.1-2010, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, the 2009 *International Energy Conservation Code* (IECC), and various state energy codes allow a significant increase (about 30%) in allowable U-factor when the exterior walls incorporate thermal mass such as concrete or masonry. The 2010 California Energy Code (CEC) divides the state up into 16 climate zones (compared to ASHRAE's 8 zones for the entire United States), each with varying benefits in the prescriptive tables for having thermally massive walls. California even defines a mass heavy category for concrete walls about 10 in. wide and thicker, with even larger allowed increases in U-factors (an allowable increase of up to 86% compared to lightweight framed walls). However, with some exceptions, these codes and standards do not currently dictate whether the thermal mass should be located on the interior or exterior side of the insulation in the wall system. Also, they do not relate the benefit of thermal mass to many other variables, such as window-to-wall ratio or internal loads (e.g., lighting).

We have seen some exceptions to the code trends described above. The residential sections of the 2009 *International Energy Conservation Code* (2009 IECC), Table R402.1.1, do require about 25% more insulation for mass walls where insulation is placed on the interior side of

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the mass wall. This indicates that the code assumes that thermal mass has more of an energy benefit when located inboard of the insulation. The 1989 Model Energy Code as reported by Christian (1991) had separate U-factor tables to distinguish the benefit of having the insulation on the exterior of the mass, however, that distinction was not incorporated into ASHRAE 90.1. The *2010 Oregon Energy Efficiency Specialty Code*, Table 502.1.3, allows the U-factor to be 30% higher if the glazing area for the building is 15% instead of 30%, but only if the insulation is on the exterior side of the concrete, masonry, or integral (e.g., between wythes). Oregon also allows up to a 38% increase in U-factor for mass walls that have the insulation on the exterior side compared to mass walls with insulation on the interior side.

In contrast, most previous research has demonstrated the better energy performance when the mass is located on the interior side of the insulation so that it can interact more directly thermally with the interior conditioned air (Burch et al. 1984, Christian 1991; Kossecka and Kosny 1998; Marceau and VanGeem 2007; Zhu et al. 2008).

Objectives and Scope

To evaluate the relative benefit of thermal mass given variables such as location of insulation, glazing area, climate, building height, and internal loads, we conducted a parametric study using a series of energy models. The objectives of this study were as follows:

1. Verify whether the allowable increases in U-factor in the prescriptive tables of ASHRAE 90.1-2010 and 2010 CEC are justified for various climates, locations of insulation, amount of glazing area, building height, and internal loads.
2. Determine if the accuracy of the prescriptive tables can be improved to account for the relative benefit of thermal mass given variables such as location of insulation and glazing area.
3. Provide information to designers and code officials on the most important parameters to maximize the benefit of thermal mass with regards to energy efficiency and identify how the prescriptive tables in ASHRAE 90.1-2010 and most state energy codes do not currently account for these benefits or parameters.

In our study, we did not attempt to optimize the use of thermal mass in any way, such as mechanical ventilation strategies to cool or heat the mass when the outside temperatures are favorable (Christian 1991).

MODEL SETUP

Software

We used the EnergyPlus version 7.2 computer program to conduct a series of whole building energy simulations. EnergyPlus is a whole building energy simulation program, developed by the United States Department of Energy (DOE). The energy simulation takes into account the building's three-dimensional geometry, enclosure (wall, window, and roof) construction and materials, and estimates of internal loads such as lighting and space conditioning. EnergyPlus has been validated based on various test standards, such as ASHRAE Standard 140 and ASHRAE Research Projects 865 and 1052.

Reference Building Model

We used the EnergyPlus commercial reference building model for a medium office building as a basis for our comparison. The medium office is three stories, has a floor area of 53,628 square feet (4982 square meters) and a floor-to-floor height is 9 ft (2.74 m). The commercial reference building models were developed by the US DOE in conjunction with three of the national laboratories: the National Renewable Energy Laboratory, Pacific Northwest National Laboratory, and Lawrence Berkeley National Laboratory. The models were created to represent typical buildings in the United States for the purpose of having a benchmark to assess the benefit of various energy efficiency design strategies.

The reference building model inputs were derived from ASHRAE Standards 90.1-2004, 62.1-2004, and 62-1999 for new construction (guidelines for energy efficiency and ventilation). As described in the following sections, we modified some of the model parameters to assess the effect of thermal mass in buildings. We also revised the insulation levels and glazing performance characteristics to comply with ASHRAE Standard 90.1-2010 or the 2010 CEC requirements.

Model Setup—Wall Assemblies

We started with two basic exterior wall assemblies: a massive and lightweight assembly. The massive assemblies have a 6 in. thick concrete back-up wall and the lightweight assemblies have a gypsum-sheathed light gauge steel-framed back-up wall.

We then modified the insulation location within those assemblies. For the massive wall assemblies, we modeled the buildings with insulation at either the exterior or interior side of the back-up wall. For the lightweight wall assemblies, we modeled insulation in the stud cavity only, however, we adjusted the conductivity so that the insulated stud cavity included the code required amount of continuous insulation (i.e., the steady-state U-factor was equivalent to that of the massive wall). The insulation amount varied in all cases to create wall assemblies that are compliant with prescriptive ASHRAE 90.1-2010 or the 2010 CEC requirements for mass walls.

The exterior wall cladding in all cases was modeled as 5/16 in. (8 mm) cement board siding. Although this cladding is not necessarily typical of office buildings, we selected this cladding because it is relatively lightweight and radiates solar heat gain toward the interior with a minimal time delay. This also keeps factors such as surface emissivity constant between all of our iterations.

Table 1 summarizes the basic wall assemblies that were used in our EnergyPlus simulations. Materials are listed from exterior to interior. Insulation thicknesses are not listed because, as described later in this paper, we varied the thicknesses to meet prescriptive code requirements based on the climate zone location.

MODEL ITERATIONS

We applied the three wall assembly types listed in Table 1 to the medium office building to determine the relative impact of thermal mass position on building energy consumption. We specifically analyzed the effect of climate, glazing, building height, and interior loads. The following sections describe our setup of the iterations.

Effect of Climate

We performed annual simulations using time-varying exterior conditions, including temperature and solar radiation, based on typical meteorological year weather data for the following climate zones:

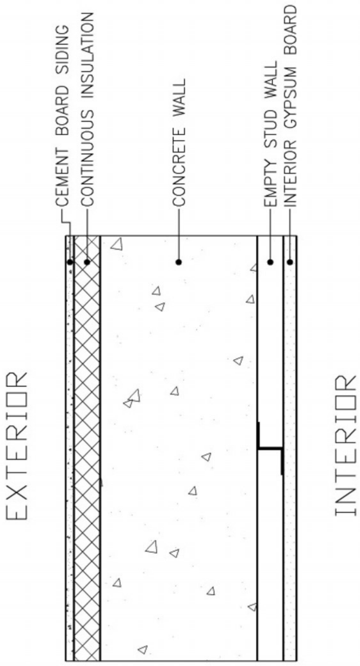
- ASHRAE Climate Zone 5A (e.g., Chicago, Illinois)
- ASHRAE Climate Zone 2A (e.g., Houston, Texas)
- California Climate Zone 3 (e.g., San Francisco, California)
- California Climate Zone 9 (e.g., Los Angeles inland region or Pasadena, California)

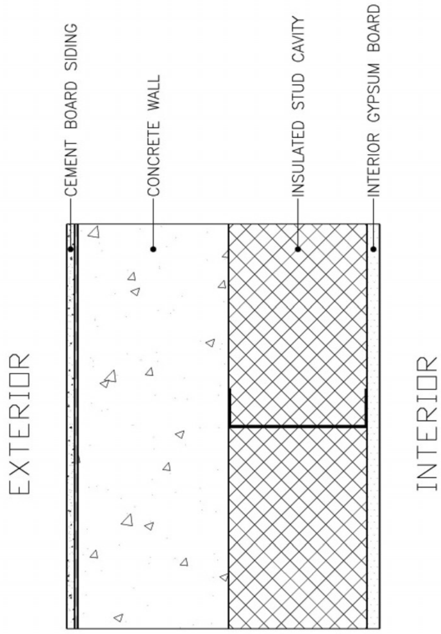
All other building geometries, components, and systems were unchanged between model iterations. We selected these climate zones to encompass the cold and warm climate extremes in the continental United States, as well as some moderate climates.

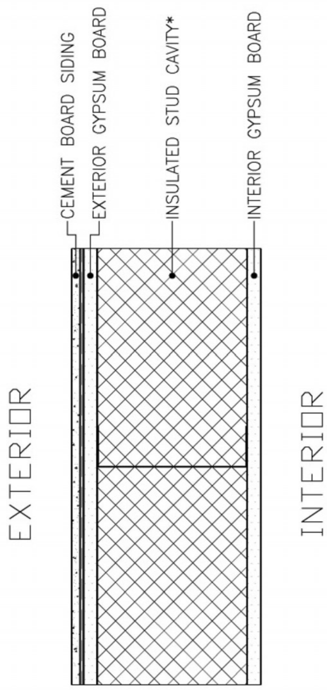
Table 2 summarizes the model iterations performed to determine the effect of climate and insulation position on en-

Table 1. Basic Wall Assemblies

Massive Wall—Exterior Insulation	Massive Wall—Interior Insulation	Lightweight Wall
• Cement board siding	• 5/16 in. (8 mm) Cement board siding	• Cement board siding
• Continuous Insulation	• 6 in. (150 mm) thick concrete wall	• 1/2 in. (13 mm) gypsum board
• 6 in. (150 mm) thick concrete wall	• Fiberglass insulation between steel studs at 16 in. (406 mm) o.c. (includes effect of thermal bridging of the studs)	• Fiberglass insulation between steel studs at 16 in. (406 mm) o.c. (conductivity reduced to include Code required amount of continuous insulation)
• 1 in. (25.4 mm) thick empty stud wall	• 1/2 in. (12.7 mm) gypsum board	• 1/2 in. (12.7 mm) gypsum board
• 1/2 in. (12.7 mm) gypsum board		







ergy consumption in buildings. Also included in Table 2 are the prescriptive maximum U-factors for the various wall assemblies.

For each wall assembly listed in Table 1, we calculated the insulation layer conductivity required to achieve the U-factors listed in Table 2.

Effect of Glazing

We also considered the effect of increasing both the glazing area and glazing performance. The medium office reference building has a 33% window-to-wall area ratio. For each climate zone, we increased the window-to-wall area ratio to 40% and 50%, representing a 21% and 52% respective increase in glazing. We chose 40% window-to-wall area ratio as a threshold for comparison because 40% is typically the current maximum glazing area allowed by most energy codes on a commercial building where you can still use the prescriptive tables to show envelope compliance. We also performed the same analysis with a 20%, 50%, and 60% glazing area ratio to see if any trends emerged.

In addition to the amount of glazing, we reviewed the effect of using better windows with lower U-factors for the case with 33% window-to-wall area ratio. Table 3 summarizes the glazing performance parameters used in our models that represent prescriptive U-factors for double glazed units and achievable U-factors for triple glazed units in a thermally broken aluminum frame. The U-factor of 0.55 is the maximum allowed in Climate Zone 5, but exceeds the requirement in Climate Zones 2 and 3 where non-thermally broken aluminum frames are allowed.

Effect of Building Height

We also considered the effect of building height on energy use. We increased the multiplier for thermal zones at the middle floor of the medium office building to 10. This effectively models a building with twelve stories instead of three. We wanted to determine the effect of the roof-to-wall area ratio on energy consumption and how that impacts the relative benefit of thermal mass compared to a lightweight wall.

Effect of Internal Loads

We reduced the electrical equipment loads and lighting by half to see if the effectiveness of thermal mass is also similarly reduced. Reducing lighting and electrical equipment loads reduces the internal heat generated by the equipment. This reduced internal heat load decreases cooling demand in summer but increases heating demand during winter.

MODEL RESULTS AND DISCUSSION

We calculated the annual and peak energy use for each model case. We considered the lightweight wall models to be the baseline cases. We then compared the massive wall model results to the lightweight model results to assess the relative change. We summarize and discuss the results in the next sections.

Effect of Climate

Tables 4 and 5 summarize the results of our analysis of the effect of climate zone on buildings with mass and lightweight wall assemblies.

Table 2. Prescriptive Code Requirements

Climate Zone	Massive Wall—Interior or Exterior Insulation		Lightweight Wall	
	Prescriptive Effective R-Value	Prescriptive U-Factor	Prescriptive Effective R-Value	Prescriptive U-Factor
ASHRAE CZ 5A	11.1 h·ft^2·°F/Btu	0.09 Btu/h·ft^2·°F	15.6 h·ft^2·°F/Btu	0.064 Btu/h·ft^2·°F
	2.0 m^2·K/W	0.511 W/m^2·K	2.8 m^2·K/W	0.363 W/m^2·K
ASHRAE CZ 2A	6.6 h·ft^2·°F/Btu	0.151 Btu/h·ft^2·°F	8.1 h·ft^2·°F/Btu	0.124 Btu/h·ft^2·°F
	1.2 m^2·K/W	0.857 W/m^2·K	1.4 m^2·K/W	0.704 W/m^2·K
CA CZ 3	3.7 h·ft^2·°F/Btu	0.268 Btu/h·ft^2·°F	12.2 h·ft^2·°F/Btu	0.082 Btu/h·ft^2·°F
	0.7 m^2·K/W	1.522 W/m^2·K	2.1 m^2·K/W	0.466 W/m^2·K
CA CZ 9	2.3 h·ft^2·°F/Btu	0.440 Btu/h·ft^2·°F	16.1 h·ft^2·°F/Btu	0.062 Btu/h·ft^2·°F
	0.4 m^2·K/W	2.498 W/m^2·K	2.8 m^2·K/W	0.352 W/m^2·K

Table 3. Glazing Performance Inputs

Climate Zone	Double Glazed		Triple Glazed		Prescriptive SHGC
	U-factor, Btu/h·ft^2·°F	U-factor, W/m^2·K	U-factor, Btu/h·ft^2·°F	U-factor, W/m^2·K	
ASHRAE CZ 5A	0.55	3.12	0.39	2.21	0.40
ASHRAE CZ 2A					0.25
California CZ 3					0.41

Table 4. Annual Heating & Cooling Energy Use and Percentage Difference Compared to Baseline

Climate	Wall Type	Heating		% Difference in Heating	Cooling		% Difference in Cooling
		MJ/m²	kBtu/ft²		MJ/m²	kBtu/ft²	
ASHRAE CZ 5A: Chicago, IL	Lightweight	231	20	—	55	5	—
	Mass—Exterior Insulation	197	17	–14.5%	50	4	–9.1%
	Mass—Interior Insulation	221	19	–4.1%	51	5	–7.8%
ASHRAE CZ 2A: Houston, TX	Lightweight	63	6	—	147	13	—
	Mass—Exterior Insulation	45	4	–28.5%	135	12	–8.2%
	Mass—Interior Insulation	51	4	–19.6%	138	12	–6.3%
CA CZ 3: San Francisco, CA	Lightweight	80	7	—	46	4	—
	Mass—Exterior Insulation	52	5	–34.7%	40	3	–13.0%
	Mass—Interior Insulation	57	5	–28.5%	39	3	–13.5%
CA CZ 9: Los Angeles Inland, CA	Lightweight	28	3	—	79	7	—
	Mass—(No Insulation Required)	13	1	–53.8%	70	6	–10.9%

Table 5. Total Building Annual Energy Use and Percentage Difference Compared to Baseline

Climate	Wall Type	Total Building Energy		% Difference in Total Building Energy
		MJ/m²	kBtu/ft²	
ASHRAE CZ 5A: Chicago, IL	Lightweight	676	60	—
	Mass—Exterior Insulation	692	61	–5.9%
	Mass—Interior Insulation	651	57	–2.2%
ASHRAE CZ 2A: Houston, TX	Lightweight	592	52	—
	Mass—Exterior Insulation	615	54	–5.2%
	Mass—Interior Insulation	583	51	–3.7%
CA CZ 3: San Francisco, CA	Lightweight	498	44	—
	Mass—Exterior Insulation	528	47	–6.7%
	Mass—Interior Insulation	493	43	–5.8%
CA CZ 9: Los Angeles Inland, CA	Lightweight	485	43	—
	Mass—(No Insulation Required)	510	45	–5.0%

The results presented in Tables 4 and 5 show that massive walls perform better than lightweight walls in all climates. The massive outperform the lightweight cases even with U-Factors that are 40% higher (allowed by ASHRAE prescriptive code tables) or 600% higher (allowed by California prescriptive code tables), than the lightweight wall U-factors.

The results in Table 5 show that positioning the mass so that the insulation is on the exterior side of the mass significantly outperforms the cases where the insulation is placed on the interior side of the mass. For example, in Climate Zone 5A, the building with insulation at the exterior side of the massive wall uses 3.7% less energy on an annual basis than the same building with insulation positioned at the interior side of the massive wall.

For all four climate zones analyzed, a building with insulation at the exterior side of the thermally massive backup wall uses approximately 1% to 4% less energy annually than buildings where the insulation is positioned at the interior side, as shown in Table 5. When the insulation is inboard of the thermally massive wall, the mass is able to absorb and store heat from solar radiation. However, during cold winter days, it is disconnected from the interior and so stays colder longer. This delays the benefit of solar radiation when it is cold and heating is called for by the HVAC systems, resulting in higher heat losses during heating periods. Thermal mass on the exterior side of the insulation can also act as a cold sink. For example, if the outside temperature is 75°F (24°C), but the thermal mass is 60°F (16°C) due to night cooling, if you are heating the building interior to 70°F (21°C), you can actually lose heat through the exterior walls (to the thermal mass), even though it is warmer outside than inside.

Tables 4 and 5 demonstrate that the code allowed insulation reductions for massive walled assemblies are justified. However, it also shows that the code should consider allowing even higher reductions for mass walls when the insulation is placed on the exterior side of the thermal mass.

One interesting point to note from Tables 4 and 5 is that for Climate Zone 9, the massive wall assembly meets the code prescribed U-factor without any insulation. Therefore, the total annual energy use is the same for both the massive wall cases.

We also separated out the annual heating and cooling loads and compared the massive wall buildings with the lightweight wall buildings in Table 5. The results show similar trends, where the cases with exterior insulation outperform the interior insulation cases, however the difference between the two is an order of magnitude greater than when comparing total annual energy use for the same cases. This is because of the effect of large lighting and equipment loads, which stay constant between all of the cases we modeled.

Looking specifically at annual heating loads in the colder climate zone (CZ 5A), the exterior insulation case uses 10% less heating energy annually than the interior insulation case. In the warmer climate zone, this difference in heating is less pronounced (only a 6% difference).

When considering annual cooling loads in the colder climate zone, the exterior insulation cases only use about 2% less cooling energy annually, while in a warmer climate zone there is almost no difference. These results indicate that location of the insulation primarily affects the efficiency of the thermal mass for heating loads versus cooling loads.

Peak Loads

Table 6 shows the peak heating and cooling loads and the percentage compared to the baseline cases.

The results presented in Table 6 summarize how massive walls can reduce peak heating or cooling demand in the three climates studied. Massive walls lower peak heating or cooling demand by up to 15% compared to lightweight walls.

In all cases, mass on the interior side of the insulation outperforms mass on the exterior side by about a 5% additional reduction in peak loads. This benefit of reducing peak demand of mass walls compared to lightweight walls is not currently accounted for in the code. Reducing peak loads results in smaller physical equipment sizes, generally lower installation and maintenance costs, and higher efficiencies.

Additionally, since mechanical engineers use peak load calculations to size mechanical equipment, they may be oversizing the equipment if not considering the effect of building thermal mass.

EFFECT OF GLAZING

Glazing Area—Total Annual Energy Results

Figures 1–3 summarize the results of our analysis of the effect of glazing area on buildings with mass versus lightweight wall assemblies. The figures show the total annual energy use according to the window-to-wall area ratio for each climate zone.

Table 6. Peak Heating or Cooling Demand and Percentage Difference Compared to Baseline

Climate	Wall Type	Electricity Peak Demand, kW	% Reduction of Peak Demand
ASHRAE CZ 5A: Chicago, IL	Lightweight	383	—
	Mass – Exterior Insulation	355	–7.4%
	Mass – Interior Insulation	376	–1.8%
ASHRAE CZ 2A: Houston, TX	Lightweight	293	—
	Mass – Exterior Insulation	263	–10.4%
	Mass – Interior Insulation	274	–6.6%
CA CZ 3: San Francisco, CA	Lightweight	262	—
	Mass – Exterior Insulation	223	–15.0%
	Mass – Interior Insulation	234	–11.0%
CA CZ 9: Los Angeles Inland, CA	Lightweight	111	—
	Mass – (No Insulation Required)	101	–9.5%

The results from Figures 1–3 show the following four trends when increasing the window-to-wall area ratio:

- The exterior insulation cases consistently outperform the interior insulation cases for mass walled buildings in all climate zones for all simulated glazing percentages.
- Increasing the glazing area results in a roughly linear increase in annual energy use, though the code prescriptive tables are only allowed currently for cases up to 40% glazing area.
- The difference in annual energy use between the lightweight and massive walled buildings decreases as the glazing area increases.
- The mass wall with higher glazing areas outperforms the lightweight wall with lower glazing areas. For example, in Climate Zone 5A, a building with insulation on the exterior of mass walls with 60% glazed area outperforms a building with 20% glazed area with lightweight walls.

The first trend was previously discussed in Section 4.1, and holds true even at varying glazing area amounts.

The second trend emerges when comparing the total annual energy use to the window-to-wall area ratio. We see that for each wall type, the annual energy use increases linearly as the glazing area is increased. For example, in Climate Zone 2A the lightweight walled building with 40% glazing uses approximately 7.7% more energy than the massed wall (exterior insulation) with 33% glazing and about

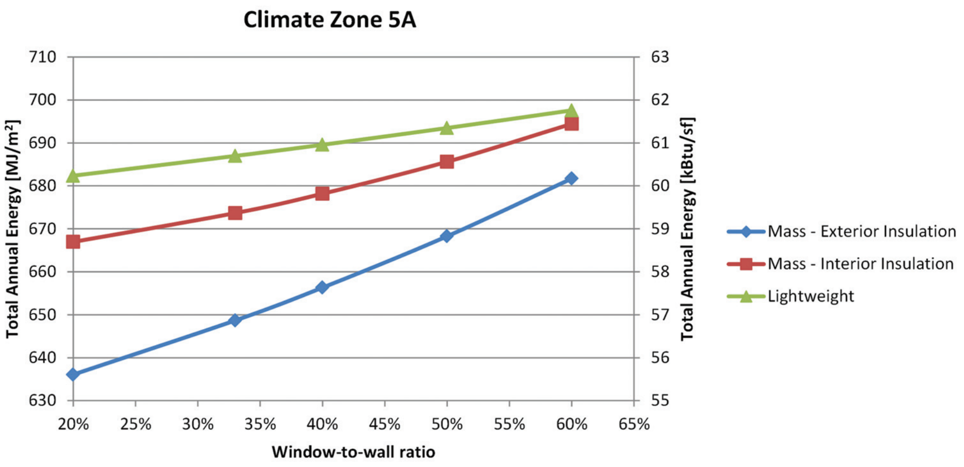


Figure 1 *Effect of glazing area on total annual energy use compared to baseline (Climate Zone 5A).*

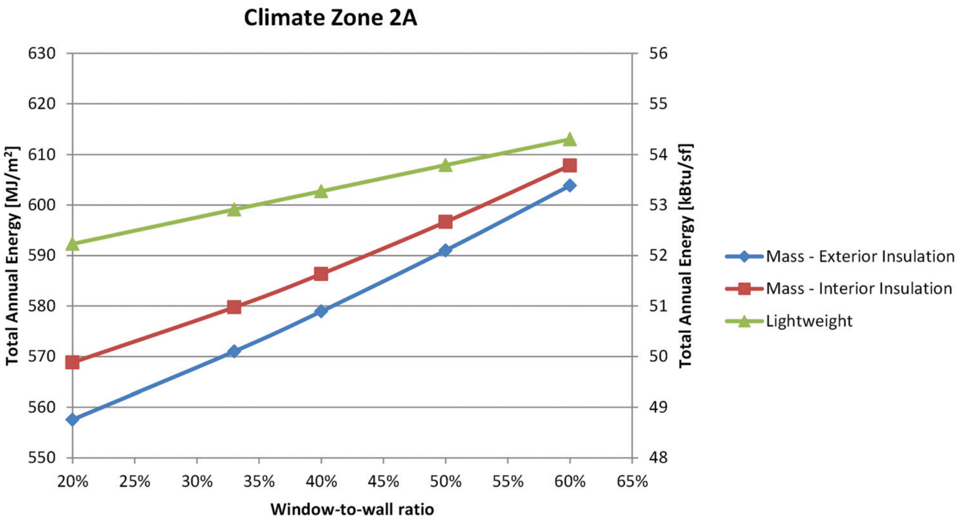


Figure 2 *Effect of glazing area on total annual energy use compared to baseline (Climate Zone 2A).*

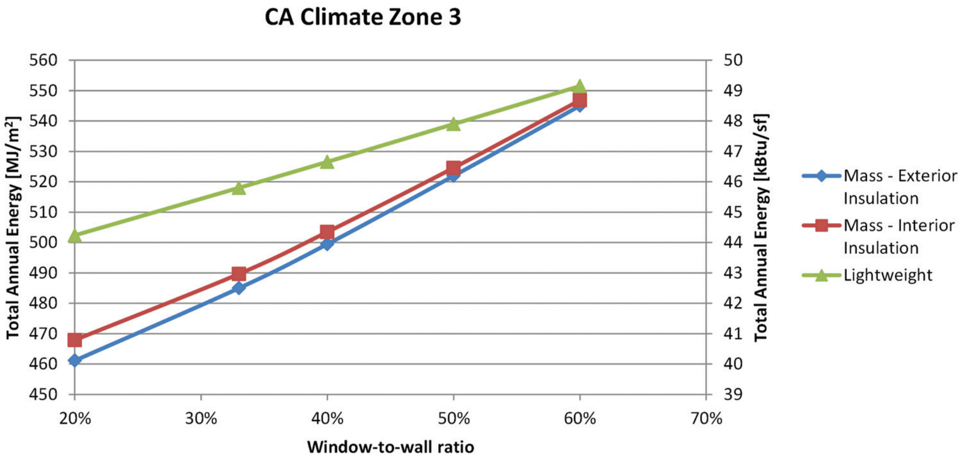


Figure 3 *Effect of glazing area on total annual energy use compared to baseline (CA Climate Zone 3).*

8.7% more energy if the window area of the massed wall building is decreased to 20%. Yet all of those cases are allowed and considered equal by the prescriptive tables in the code.

The third trend is that as glazing area increases, the total energy use converges between the three cases: lightweight, massive with exterior insulation, and massive with interior insulation. For example, in Climate Zone 3, the three cases converge at about 60% glazing area. In the colder Climate Zone 5A, the convergence occurs at a glazing area greater than 60%. At 60% glazing, the difference between the massive wall with exterior insulation and lightweight wall is still about 3%.

The fourth trend is that a mass wall with higher glazing areas can use less energy than a lightweight wall with lower glazing areas. For example, in the Climate Zone 5A, the mass wall with exterior insulation and 60% glazing uses less energy than the massive wall with interior insulation and 40% glazing. It is also uses less energy than the lightweight wall case with only 20% glazing. This indicates that the thermally massive walls can in essence be used to offset the higher glazing areas. However, according to current codes a mass wall with 60% glazing area does not comply with the prescriptive compliance path of the code, while a lightweight wall with 20% glazing does comply.

Glazing Area—Heating and Cooling Energy Results

Figures 4 and 5 show the percentage reduction in annual heating and cooling loads of the mass walled buildings compared to the lightweight walled buildings.

The figures show that for heating and cooling loads, a building in Climate Zone 3 has the greatest reduction in heating (10% to 50%) and cooling (4% to 19%) energy use, at all glazing area ratios. A building in Climate Zone 2A uses from 9% to 40% less heating energy than the baseline, which makes sense because it is a warmer climate. Conversely, a building in Climate Zone 5A uses from 2% to 12% less cooling energy than the baseline case, because it is a colder climate.

The magnitude of energy savings when comparing only the percentage change in heating or cooling loads exceeds the total energy load, because the total includes lighting and equipment loads which remain constant between cases.

Looking at the breakdown by climate, it is apparent that Climate Zone 3, the mild climate, shows the greatest heating and cooling load percent reductions for the mass walls compared to lightweight walls. For example, for heating loads, the reduction compared to the lightweight case ranges from 10% to 40% and for cooling loads ranges from 2% to 15%. However, this is because the heating and cooling loads are very small in a mild climate. For example, a 2.0 MJ/m^2 (0.18 kBtu/ft^2) reduction in Climate Zone 5A, where the heating load is 200.7 MJ/m^2 (17.7 kBtu/ft^2), results in a modest percentage change compared to Climate Zone 3 where the heating load is only about 60.2 MJ/m^2 (5.3 kBtu/ft^2).

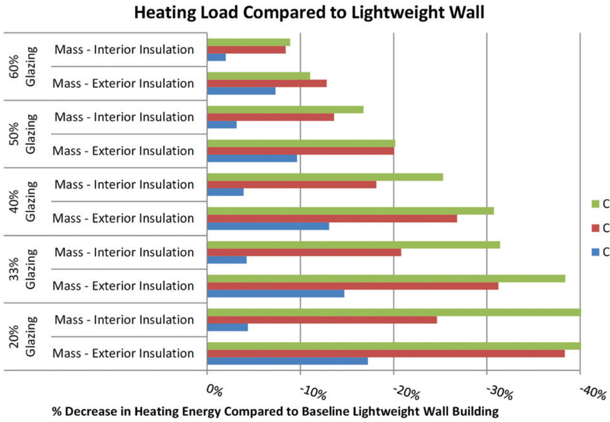


Figure 4 *Percentage difference in annual heating load of the mass walled building compared to baseline, given different glazing areas.*

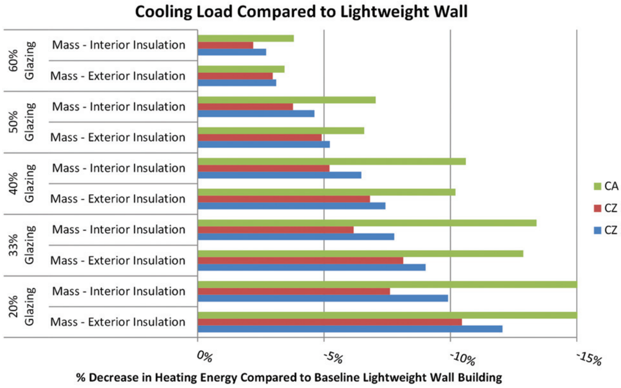


Figure 5 *Percentage difference in annual cooling load of the mass walled building compared to baseline, given different glazing areas.*

Glazing Performance—Total Annual Energy Results

Figures 6 through 8 show the effect of including triple glazed windows compared to double glazed (lower U-factor for windows per Table 3) in the building in Climate Zones 5A, 3A, and CA Climate Zone 3, with a 33% window-to-wall area ratio.

The results show that with the exception of Climate Zone 5A, the lightweight walled building benefits most from the upgrade to triple glazed windows. However, the massed wall buildings still out-perform the lightweight walled building. Also, insulation placed on the exterior side of the mass outperforms the case with insulation on the interior side of the mass, most significantly in the colder Climate Zone 5A. The heating and cooling energy data shows that this is because the better windows reduce heating loads by a larger amount than cooling loads (given the same solar heat gain coefficients), so that magnifies the benefit of mass on the interior side in heating dominated climates. The results also show that the better win-

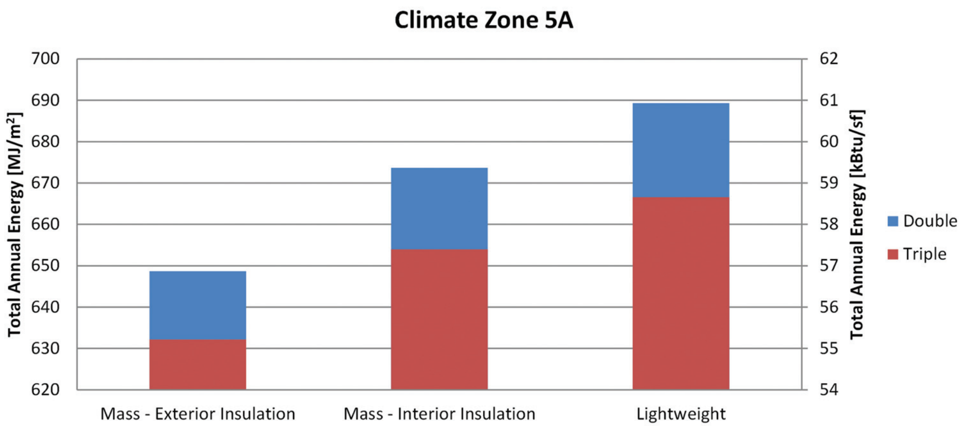


Figure 6 *Effect of including triple glazed windows on total annual energy use compared to double glazed (Climate Zone 5A).*

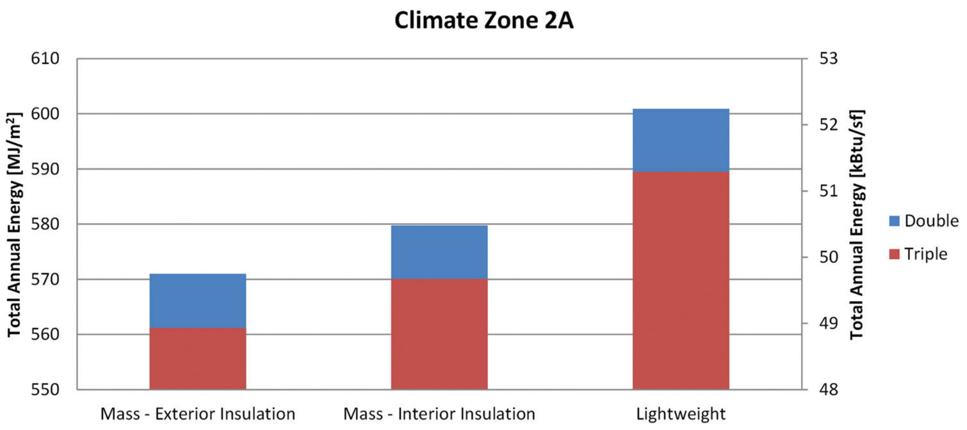


Figure 7 *Effect of including triple glazed windows on total annual energy use compared to double glazed (Climate Zone 2A).*

dows could offset the increased energy use from having a larger glazed area. For example, comparing Figures 1 and 6 shows that in Climate Zone 5A, a massed wall building with insulation on the exterior side of the mass, and with a 33% glazed area, outperforms the same building with 20% glazed area if the windows are improved to triple glazed. The benefit of using better windows combined with a thermal mass strategy is not currently accounted for in the prescriptive tables of the code.

Effect of Building Height

Figure 9 summarizes the results of our analysis of the effect of building height on buildings with mass and lightweight wall assemblies in various climates. The figures show the percentage difference in total energy for the mass wall building compared to the lightweight wall buildings, according to climate zone and building height. The results show less than a 1% relative difference due to building height between a building with mass wall and lightweight wall assemblies.

When comparing the results of a 3 story building to a 12 story building, some trends discussed in earlier sections are similarly true. For example, the exterior insulation cases outperform the interior insulation cases for massive walled buildings.

While the 12 story building cases all use more energy than the 3 story cases, we can compare each to their respective lightweight cases to extract some trends. For all climate zones, the 12 story building percent reduction in energy for the massive cases are about 1% better than for the 3 story building cases. This slight difference can be attributed to the increased wall-to-roof area for the taller building. This amplifies the benefit of the thermal mass in the walls, and at the same time diminishes the effect of the roofing assembly.

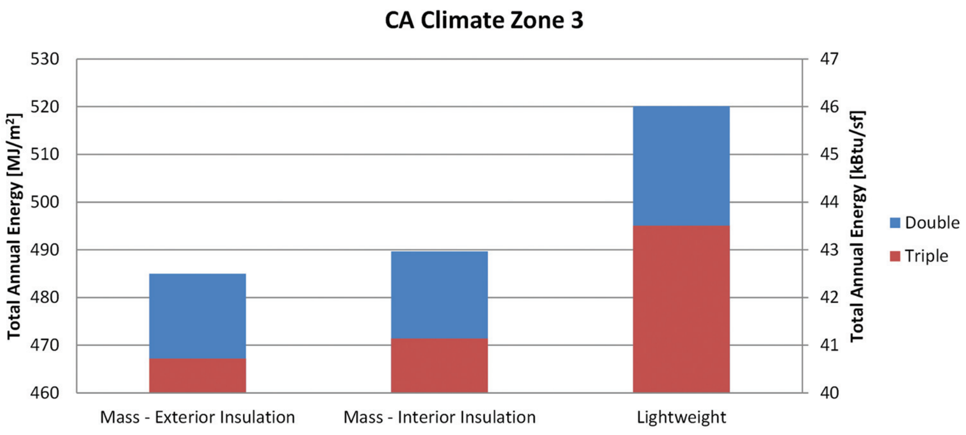


Figure 8 *Effect of including triple glazed windows on total annual energy use compared to double glazed (CA Climate Zone 3).*

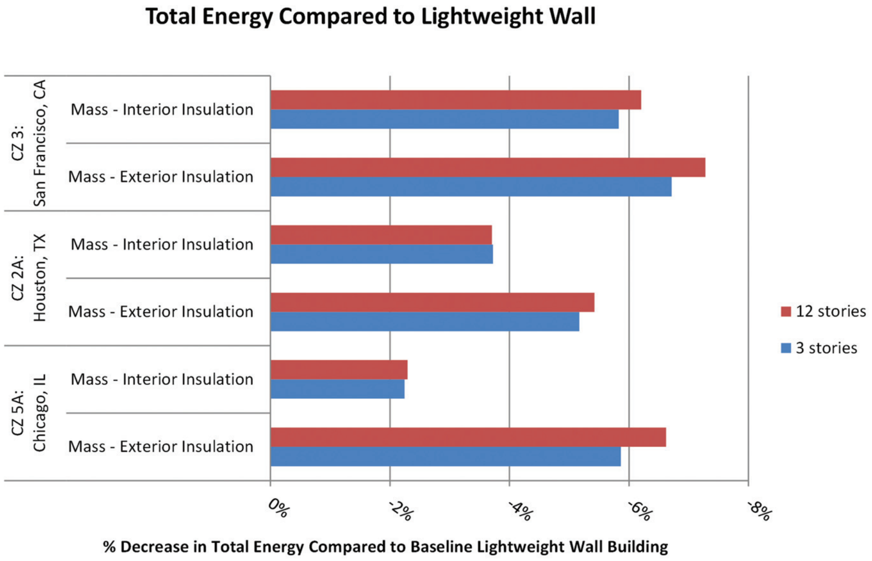


Figure 9 *Effect of building height on relative benefit of mass walled buildings compared to baseline.*

Effect of Internal Loads

Figures 10 to 12 summarize the results of our analysis of the effect of internal loads on buildings with mass and lightweight wall assemblies. From this figure, we see that the reduction in internal loads has a greater effect in the warmer climate zone.

Figures 11 and 12 show the annual heating and cooling energy results.

The heating energy increases by 24% to 39%, with the larger differences seen in the colder climate zone.

The cooling energy decreases by 18% to 24%, with the larger differences seen in the warmer climate zone.

We see that the total energy savings is largest in the warmer climate zone when reducing lighting and equipment loads by 50%. This is attributed to the reduced cooling load in these climates resulting from the reduced radiant heat energy from smaller lighting and equipment loads. When we separate out and analyze the annual heating and cooling loads, we see that, as anticipated, the heating loads increase, while the cooling loads decrease.

One note to add here is the difference in the cost of different energy sources. Typically a building uses natural gas for heating, and internal loads such as lighting and equipment use electricity. Since natural gas is currently cheaper than electricity, the heating cost will be much lower than the cost for internal loads from equipment. Therefore, reducing the internal loads by 50% will result in a significant cost savings, perhaps enough to offset the increased heating required during the winter.

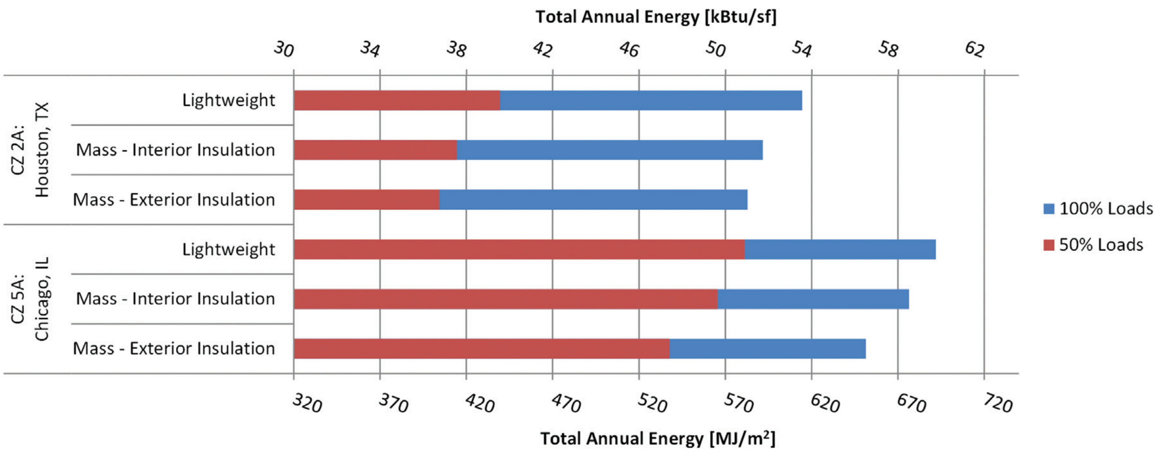


Figure 10 *Total annual energy at reduced internal loads compared to baseline.*

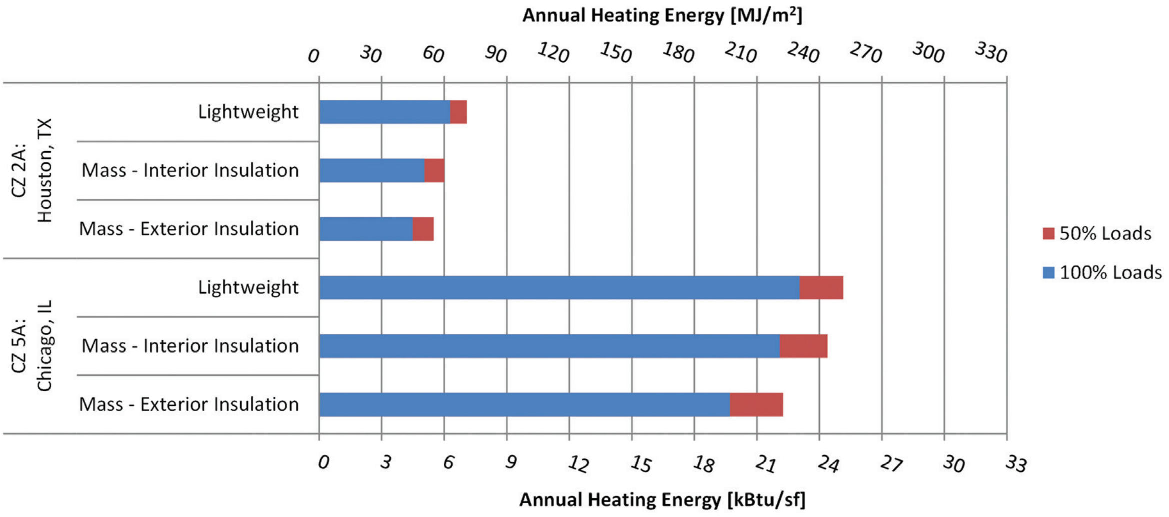


Figure 11 *Total heating energy at reduced internal loads compared to baseline.*

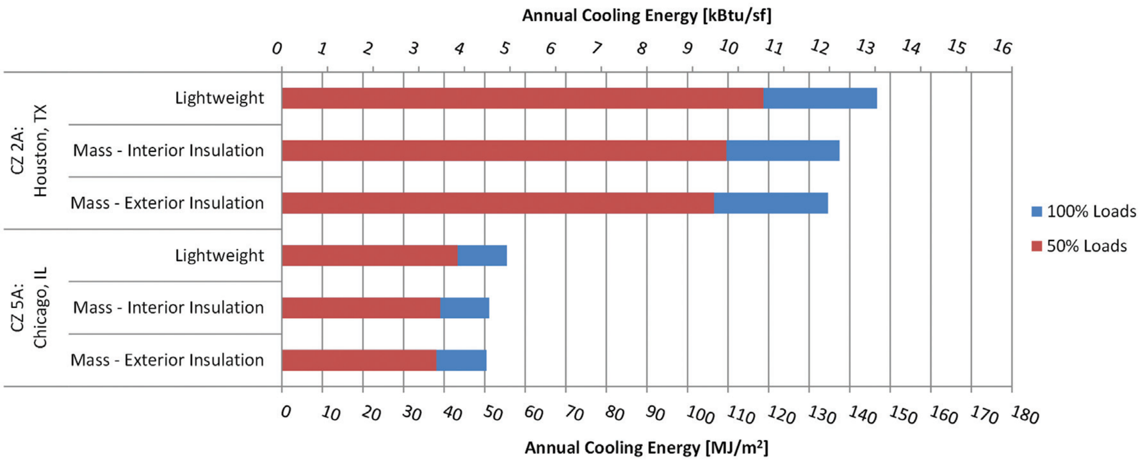


Figure 12 *Total cooling energy at reduced internal loads compared to baseline.*

CONCLUSIONS AND RECOMMENDATIONS

Based on our analysis, we conclude the following:

- From a total heating/cooling energy standpoint, buildings with mass walls outperform those with lightweight walls, despite the higher U-factors allowed by code for mass walls compared to lightweight walls. The allowed higher U-factors are justified for the all the cases and variations we studied, even for the California climate zone 9 where insulation was not even required in the mass walls.
- Positioning insulation at the exterior of the massive wall results in greater energy savings than insulation at the interior side in all the cases and climate zones we studied. The effect is stronger in heating climates, up to 10% reduced heating load and almost 4% reduction in total building energy loads compared to cases where the mass is positioned on the exterior side of the insulation. We recommend that future editions of ASHRAE 90.1 and international and state energy codes provide a larger benefit (increased U-factor) for mass on the interior side of the wall insulation.
- Our study confirmed that mass walled buildings also reduce peak loads by up to 15%, the benefit for mass on the interior side of the insulation being about 5% higher reduction in peak loads compared to mass on the exterior side of insulation. This reduction in peak loads is not accounted for in the prescriptive method of ASHRAE 90.1-2010 and state energy codes, but we recommend that it be considered for incorporation, particularly for the interior mass case. In addition, mechanical engineers may oversize equipment if their load calculations do not consider the effects of thermal mass and the location of that mass with respect to the insulation.
- The difference in annual energy use between the lightweight and massive walled buildings decreases to the point of convergence as the glazing area increases, however this does not occur until reaching much larger glazing areas than the 40% maximum allowed by current codes for prescriptive compliance.
- Mass walled buildings with higher glazing areas significantly outperform lightweight walled buildings with lower glazing areas, indicating that the mass can be used as an energy efficient strategy to offset high glazing areas. We recommend that future editions of ASHRAE 90.1 or state energy codes allow a higher glazed area for buildings with mass walls, or alternatively lower the maximum glazed area for lightweight walls that can be used with the prescriptive method of compliance.
- Lightweight walled buildings appear to benefit more from windows with a lower U-factor than mass walled buildings as a percent reduction in total energy, but mass walled buildings still out-perform lightweight walled buildings (only the relative benefit of having the mass decreases). Also, windows with a lower U-factor benefit all buildings in all climates, and therefore the use of a better window can offset a higher glazed area. This benefit is not currently captured by the prescriptive tables in the code.
- Taller buildings have an increased wall-to-roof area ratio and therefore slightly increase the positive effect of the mass walls by reducing whole building energy use by up to an additional 1% compared to a lightweight walled building.
- Reducing internal loads (lighting and equipment) reduces the demands on the cooling system in the summer, while increasing the heating system demands in the winter. The effect on energy savings will therefore depend on the climate zone, with greater reductions in cooling dominated climates. Since the cost for heating is typically much lower than the cost for lighting and equipment, reducing internal loads may result in enough savings to offset the increased cost of heating during the winter.

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