Designing thermal mass to promote energy efficiency in buildings.

Think Thermal

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THE ENERGY CONSUMPTION of a building can be reduced by the effective placement of elements that contribute to a building's mass.

Lightweight building systems have long been considered to be less energy efficient in this regard than mass-intensive systems. That assumption was challenged by a Ryerson University research study conducted by Dr. Mark Gorgolewski (see "Framing Systems and Thermal Mass," in the January 2007 issue) that demonstrated that the quantity of mass was not the only factor in determining the overall thermal efficiency of a building system. Rather the thickness, placement and exposure of building materials with high thermal mass all impact the material's contribution to the building's energy efficiency. The Ryerson study concluded that structural steel-framed buildings can contain adequate quantities of high thermal mass materials, such as concrete, to provide equivalent energy savings to high-mass buildings.

Here, we'll extend that discussion by looking at the energy impact that the amount and placement of insulation can have for both mass and lightweight wall systems as well as the relative impact of the thermal mass contributed by floor systems. What we've discovered is that through proper material placement and the use of energy modeling as a design tool, the amount of thermal mass necessary to achieve energy benefits similar to those of concrete-framed buildings is available in steel-framed buildings without a significant increase in project cost.

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Thermal Mass: A History

Prior to the advent of modern lightweight construction, which uses materials such as plywood, gypsum wallboard and sheathing, corrugated steel decks and light-gauge steel framing, building structures and elements of solid masonry were essentially standard practice. As time has shown, these structures had the advantage of being extremely durable and redundant, capable of performing in harsh winters as well as hot and humid summers. Their thick, massive walls and interior components had significant thermal mass (also referred to as heat capacity), allowing them to store and gradually release heat over time. In winter climates heat stored during the day, when temperatures are warm (relative to night conditions) and solar gains are high, is released into the building at night. The opposite is true in the summer; walls that cool off overnight retain their "cool" during the day and help to even out peak high temperatures and solar gains during the day.

Despite these benefits, solid masonry buildings had two primary disadvantages. Although their thermal mass aided in reducing peak heating and cooling loads, these typically uninsulated buildings were still relatively inefficient compared to modern insulated construction. Second, and more timely to the demise of this construction style, were the practical limits of solid masonry construction. The growth of large cities in the early 1900s created a need to build taller buildings faster and at a lower cost than was possible with traditional building styles. For example, when completed in 1893, the Monadnock Building in Chicago was the largest office building in the world. The north half of the building, at 16 stories in height, remains one of the tallest structures in the world to be built solely from load-bearing masonry. To support the weight of the structure, the solid brick walls at the foundation level are over 1.8m (6 ft) thick. This half of the building took nearly two years to complete. In sharp contrast, the steel-framed Empire State Building in New York City, the tallest building in the world (102 stories) from its completion in 1931 until 1972, was built in just over a year. This comparison, while extreme, highlights the limitations of solid masonry construction and the need to use alternate structural systems to support the needs of modern buildings.

The Thermal Challenge

Although for a time steel-framed buildings were still constructed with infill (non-load-bearing) walls of solid or hollow-core masonry, by the 1950s and 1960s lightweight wall construction had all but taken over. Along with the need for increased energy efficiency came insulation in walls and roofs, which helped reduce overall energy consumption but at the same time eliminated the benefits of thermal mass. As is often the case, the industry is starting to circle back on itself and look to thermal mass as another piece in the energy efficiency puzzle. The challenge lies in determining the most effective way to make lightweight construction become "thermally massive" without affecting other performance characteristics.

To evaluate the impact of thermally massive building elements on building energy use, we evaluated a series of whole-building energy models using the Energy Plus computer program (version 6). Energy Plus is a validated whole-building simulation tool developed and maintained by the U.S. Department of Energy. The structure used in the model was a generic "medium-sized office" building, part of a suite of typical building models created by the Pacific Northwest National Laboratory (PNNL) for use in comparative energy analyses. The building is a three-story, steel-framed structure with approximately 30% glazing and 53,000 sq. ft of floor space.

The basic models in our analysis used wall, roof and window U-values based on ASHRAE Standard 90.1-2010. Simulations were run for three climate zones:

- Zone 2: Orlando, Fla.
- Zone 4: New York, N.Y.
- Zone 7: Grand Forks, N.D.

As is often the case with computer element modeling, the accuracy of energy models is more a function of inputs and assumptions than the calculation method itself. The basic equations for calculating heat losses, gains, etc. are extremely accurate and, in the case of Energy Plus, extensively tested and validated, but the accuracy of assumptions is hard to quantify. As such, energy models are better for predicting trends and performing parametric analysis of multiple options/alternates than for calculating absolute values for energy use or cost.

Wall Systems and Insulation

Recognizing the energy impact of using mass walls, ASHRAE 90.1-2010 (as well as the International Energy Conservation Code, IECC) allows for the use of higher U-values/lower R-values for mass walls as compared to lightweight walls. Mass walls are defined as walls with heat capacities exceeding (1) 143 kJ/m^2K (7 btu/ft^{2}*°F) or (2) 102 kJ/m^2K (5 btu/ft^{2}*°F) if the wall has a material unit weight less than 1,920 kg/m^3 (120 lb/ft^3). Under this definition, most concrete masonry unit walls qualify, but brick veneer over lightweight (i.e., steel stud-framed) backup walls do not. The allowable reduction in the effective R-value of building walls varies by climate zone and position of insulation, with the greatest reductions allowed when all of the mass wall insulation occurs on the exterior side of the mass.

As shown in Figure 1, when placed on the exterior of the thermal mass, insulation tends to make the interior masonry warmer and more capable of exchanging energy with the interior. Conversely, interior insulation keeps the thermal mass cold and may exacerbate heat loss from the interior. ASHRAE 90.1 and related codes and standards typically focus on thermal mass in exterior walls and do not offer guidance on the use of internal thermal mass components such as floor slabs, which do not have any exterior exposure.

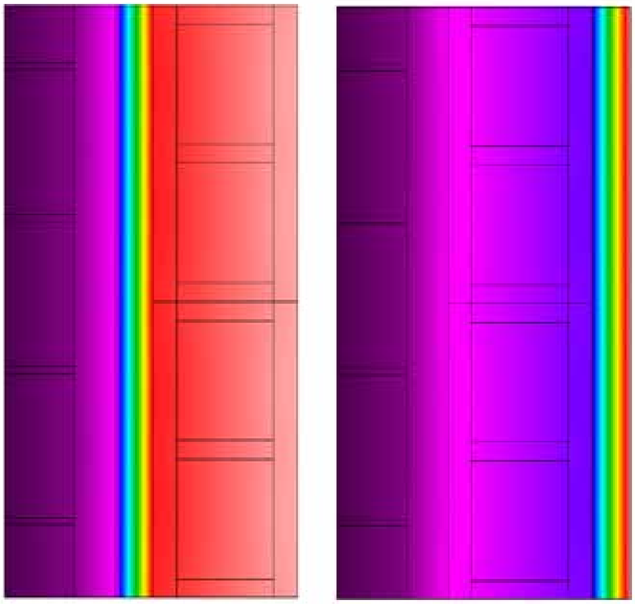


Figure 1: Temperature distribution in a brick veneer/CMU backup wall with either exterior (left) or interior (right) insulation. Dark colors are colder, light are warmer. This shows that in a steady state condition, the wall with interior insulation has a large cold thermal mass on the outboard side, whereas in the exterior insulation case the mass stays warm due to exposure to the interior.

A series of analyses were run using various levels of insulation and thermal mass in both the exterior walls and interior components (mass only). In the initial simulation, overall space conditioning use (heating and cooling) was compared for the test building using mass and lightweight walls. These results, illustrated in Figure 2, show that despite the effective R-values of the mass walls being lower (by up to 40%), overall energy use in the mass-walled buildings is actually slightly lower than for the stud-framed options. This demonstrates the important principle that the performance of thermally massive components must be evaluated on a transient basis, as heat storage and release are pro-

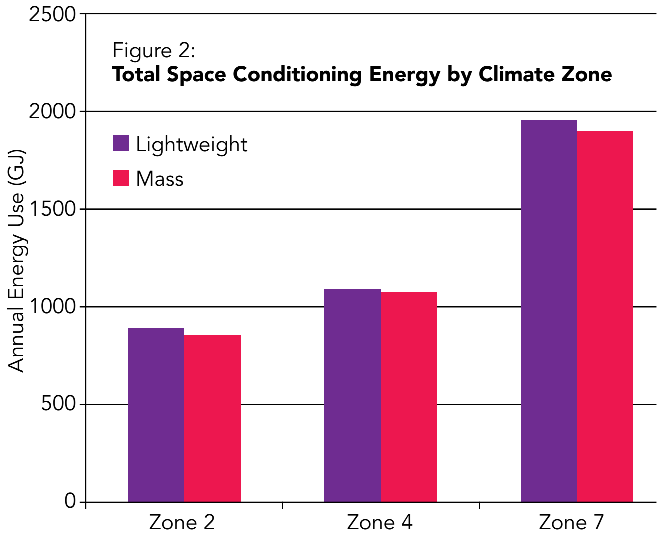


Figure 3:
Total Space Conditioning Energy by Wall Type for Climate Zone 4

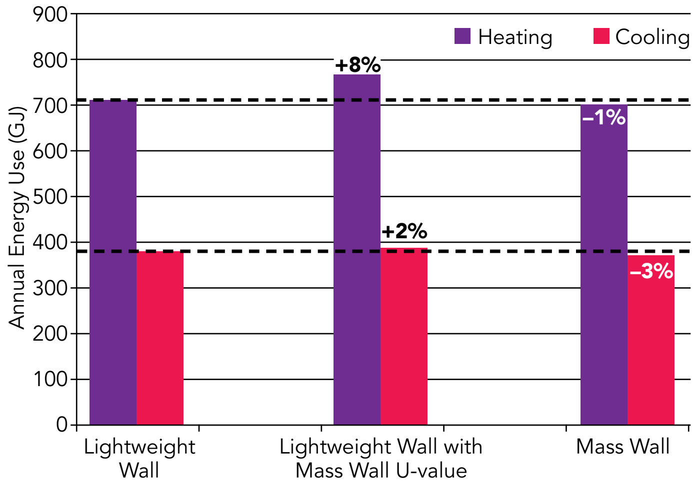


Figure 4:
Total Space Conditioning Energy by Insulation Location for Climate Zone 4

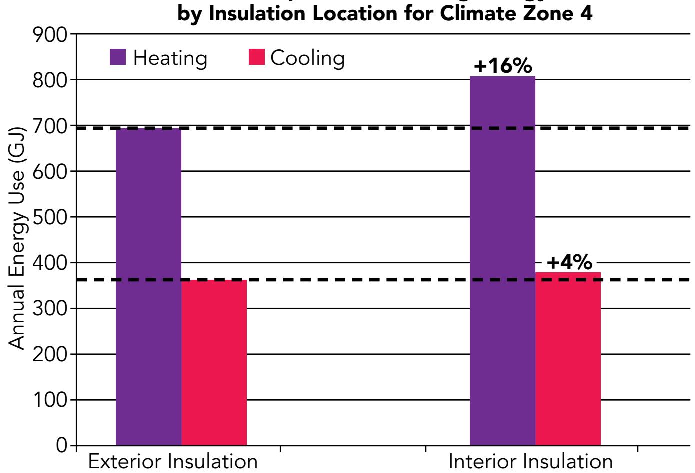
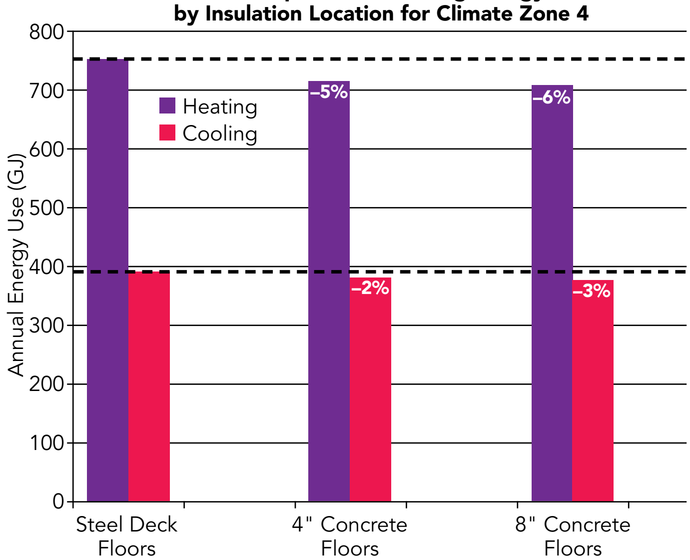


Figure 5:
Total Space Conditioning Energy by Insulation Location for Climate Zone 4



cesses that happen over time and with changing environmental conditions—unlike the steady-state descriptors of R-value and U-value, which are essentially time-independent.

Several specific cases for climate zone 4 were reviewed to determine how the amount and location of insulation affects overall space conditioning energy. These comparisons are illustrated to the left.

To demonstrate the benefits of thermal mass (as shown in Figure 3), space conditioning energy use for a lightweight-walled building with code-minimum values for insulation was compared with lightweight and mass wall systems having identical U-values. The data indicate that energy use, primarily heating, increases by approximately 8% if the mass wall R-values are used with lightweight construction. The intent is to show that the code allows the use of reduced R-values for mass walls, and that this ends up using the same or less energy as the higher R-value lightweight walls, and demonstrates the benefits of thermal mass at reducing energy use.

To demonstrate the importance of the position of insulation (Figure 4), the energy use for mass-walled buildings with interior insulation was compared to the energy use with exterior insulation (both with identical R-values). When insulation is placed on the interior of the thermal mass, heating energy demand increased by 16% and cooling energy demand by 4%. As shown in Figure 1, the exterior insulation helps to keep the thermal mass warm and allows for more efficient energy exchange with the interior. When placed on the interior, insulation separates the thermal mass from the space and creates a "cold sink" on the outside of the building that leads to heat loss from the interior for prolonged periods of time (i.e., even when exterior temperatures increase, the temperature of the thermal mass lags behind and remains colder for longer).

The previous examples show the impact of thermal mass when placed in the exterior walls (i.e., concrete masonry unit walls in place of light gage steel-framed walls). In those cases, the benefits of thermal mass are maximized when the mass is located inboard of the insulation. However, it is not always possible to achieve this. For example, in dense urban areas lot line walls are often constructed of CMUs (for fire resistance) but built from the interior, making exterior insulation impractical or impossible. In these and similar cases, it is important to look beyond the exterior walls as sources of thermal mass and more towards the building interior—where we know that it will be most effective.

Floor Systems

Space conditioning energy use was compared for the sample building, with lightweight exterior walls, for three floor configurations: steel deck only (rarely used in new construction—provided as a reference point to demonstrate the impact of the concrete in the floor system); 4-in. (100-mm) normal weight concrete on steel deck; and 8-in. (200-mm) normal weight concrete on steel deck. The results of this analysis are shown in Figure 5.

These results clearly show that the impact of thermal mass in the floors can be significant, with about 5% reduction in heating energy use just by using 4-in. concrete floors in place of lightweight floor systems. There is a point of diminishing returns after about 4 in., as energy use is only slightly reduced when the slab thickness is doubled. Since most steel-framed buildings contain concrete slabs (with 4 in. being common), they already provide thermal capacity and may not require specific mass components in the exterior walls. Further, interior partitions in stairwells, which are often concrete masonry, or interior shear walls of concrete masonry will further contribute to the thermal mass of the building and help to promote energy efficiency. The specific balance of thermal mass will depend greatly upon the building type, as tall buildings with small floor-to-wall ratios may benefit more from massive walls, or require impractical floor slab thicknesses. Designers must be cognizant of the benefits of thermal mass and understand how decisions such as exterior wall or partition type, interior floor types, etc. can impact building energy use despite being apparently disconnected from that aspect of performance.

Significant Impact

Thermal mass elements, whether in exterior walls or as interior components, can have a significant impact on space conditioning use in buildings. The impact of thermal mass will depend on many factors, including climate zone, building dimensions and most importantly the location of the mass with respect to insulation. Given that the majority of the building structure, including large components such as floors or stairwell walls, is inboard of the insulation, these elements should be considered when evaluating thermal mass benefits. Based on the analysis presented here, there is a point of diminishing returns when adding thermal mass, making comparative energy modeling an important step in the building design due to the cost impacts of adding mass to a building (increased loading, additional structural requirements, etc.). Lastly, the amount of thermal mass necessary to achieve moderate energy benefits is practically achievable in lightweight (i.e., steel-framed as opposed to concrete-framed) buildings, contrary to the typical opinion that steel-framed buildings cannot benefit from thermal mass effects without significant modification. MSC