THERMAL MASS IMPACT ON ENERGY PERFORMANCE OF A LOW, MEDIUM, AND HEAVY MASS BUILDING IN BELGRADE

by

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Heavy mass materials used in building structures and architecture can significantly affect building energy performance and occupant comfort. The purpose of this study was to investigate if thermal mass can improve the internal environment of a building, resulting in lower energy requirements from the mechanical systems. The study was focused on passive building energy performance and compared annual space heating and cooling energy requirements for an office building in Belgrade with several different applications of thermal mass. A three-dimensional building model was generated to represent a typical office building. Building shape, orientation, glazing to wall ratio, envelope insulation thickness, and indoor design conditions were held constant while location and thickness of building mass (concrete) was varied between cases in a series of energy simulations. The results were compared and discussed in terms of the building space heating and cooling energy and demand affected by thermal mass. The simulation results indicated that with addition of thermal mass to the building envelope and structure: 100% of all simulated cases experienced reduced annual space heating energy requirements, 67% of all simulated cases experienced reduced annual space cooling energy requirements, 83% of all simulated cases experienced reduced peak space heating demand and 50% of all simulated cases experienced reduced peak space cooling demand. The study demonstrated that there exists a potential for reducing space heating and cooling energy requirements with heavy mass construction in the analyzed climate region (Belgrade, Serbia).

Key words: *building, thermal mass, energy performance*

Introduction

Heavy mass materials such as stone, brick masonry and concrete have long been used in building construction worldwide. These materials have physical properties which naturally store thermal energy and buffer dynamic heat transfer interactions in their immediate environment. Commonly referred to as thermal mass, their ability to slowly absorb and re-

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lease heat affects building energy performance. Understanding of thermal mass impact on building energy consumption and demand at the earliest design stage can be very helpful in the design of high performance buildings. This paper explores, through computer dynamic thermal simulation, how heavy mass (concrete) construction affects the passive thermal behavior of a building in Belgrade, Serbia.

In the "green building" market many sophisticated energy efficient systems are applied to reduce total building energy consumption. However, passive architectural and structural features incorporated during the early design phase can reduce the building energy requirements even before energy efficient systems are applied.

It is important to note that there are other benefits that may arise from building with high thermal mass beyond energy efficiency: It is generally assumed that buildings high in thermal mass are not only less sensitive to weekly weather oscillation (with smaller indoor air temperature fluctuations), but also provide better thermal comfort to the occupants.

The thermal interaction between heavy mass construction and the external and internal environment is complex. To understand and simulate it with accuracy we must consider all modes of heat transfer, conduction, convection, radiation, heat storage and the associated long-term transient heat transfer effects. The steady-state conduction/convection formulas traditionally used for simplified calculations of building thermal loads cannot fully describe the thermal performance of heavy mass; as a result its behavior is often misunderstood or neglected from consideration during the design phase.

Thermal mass has recently become an integral part of passive building design with low temperature building heating and cooling systems (in-slab radiant heating and cooling with displacement ventilation) and solar systems.

Energy simulation tool

Predicting the effect of thermal mass on energy use and thermal comfort requires suitable energy simulation software with the following features:

– it uses a 3-D building geometry input to define surface areas and orientations with respect to one another; this enables accurate external and internal radiant heat transfer calculations which are necessary to evaluate thermal mass behavior,
– it has the ability to calculate internal and external surface temperatures, mean radiant temperatures, air temperatures and humidity, wind and buoyancy driven air movement, thermal storage, and inter-zone conduction, convection and radiation,
– it is capable of simulating cooling by natural ventilation both on schedule and by space resultant temperature,
– hourly space heating and cooling load and energy balance calculations are conducted with hourly weather data, and
– building heat transfer and energy calculations can be performed independently of mechanical system input.

The simulation software used for this study is IES Virtual Environment (VE) – module Apache Sim. This software has all of the above noted features.

Modeling methodology

This is a parametric study conducted on one building type (office building) in Belgrade, Serbia. To isolate the effect of thermal mass on the space conditioning energy and peak demands, the building mechanical systems were not simulated. The heating and cooling energy required to temper the ventilation air to the space temperature set point is included. The only adjusted parameter is the amount and location of concrete within the building. The scope of this study is to assess the passive behavior of thermal mass construction under these conditions.

The effect of thermal mass (concrete) in the building structure and envelope on annual space heating and cooling energy requirements and peak space heating and cooling demands is explored through the following steps:

(1) research previous studies and common knowledge of the impact of building thermal mass on annual space heating and cooling energy requirements and peak space heating and cooling demands,
(2) develop a simulation base model to reflect a standard office building as described in the section *Energy simulation* with lightweight (low-mass) construction and low thermal mass in the envelope; simulate the annual space heating and cooling energy requirements and peak space heating and cooling demands,
(3) copy the model from Step 2 and increase the amount of thermal mass (concrete) in the building to a medium-mass level (definition of low, medium and heavy thermal mass levels are provided in the subsection *Simulation parameters: concrete thickness and U-value*) and simulate the annual space heating and cooling energy requirements and peak space heating and cooling demands with concrete in the floor, walls and roof in the following three combinations:
   - concrete block interior walls, concrete floors and a concrete roof with insulation on the exterior side of the envelope,
   - concrete external walls, floors and roof with the insulation located on the interior side of the envelope and,
   - concrete external walls, floor and roof with the insulation located on the exterior side of the envelope,
(4) copy the models from Step 3 and further increase the amount of thermal mass (concrete) to a heavy mass level and simulate the annual space heating and cooling energy requirements and peak space heating and cooling demands with the same 3 orientations as the medium mass,
(5) conduct Steps 2 through 4 with the building's long axis aligned North-South and East-West and with both convective and radiant heat transfer as the dominant modes of space temperature control, and
(6) use Belgrade weather file for simulations in Steps 2 through 5.

Simulation results are presented and compared in terms of space energy and peak demand. To isolate the passive effects of thermal mass from any mechanical HVAC system assumptions, no mechanical systems are modeled. Rather, the annual space heating and cooling energy requirements and peak space heating and cooling demands are calculated and compared between cases in terms of energy specific intensity, kWh/m^2 year and W/m^2, respectively.

Literature review

A review of existing information found that many research projects and simulation studies have been conducted, but were focused on thermal mass in conventionally designed buildings that have concrete floor slabs with lightweight envelopes (residential high-rise buildings). Heavy mass construction is often associated with passive solar design. All sources conclude that the thermal storage of building mass decouples the building thermal load profile from the operation of the equipment, and that heavy mass buildings experience more stable indoor temperatures than lightweight buildings.

Building mass thermal behavior and occupant comfort

The University of Maryland states that the use of thermal mass in a building cannot increase or decrease the total amount of energy available or affect the long term heat gain or loss of the building. This suggests that, without considering time related effects, there would appear to be no benefit or limitation associated with thermally massive construction. However, they conclude that the thermal storage capacity interacts with cyclic thermal loads, and thermal mass does reduce extreme indoor temperatures [1].

Szokolay features massive construction in his chapter on the dynamic response of buildings and says that the high thermal capacity of thermal mass affects the timing of heat transfer, as well as the magnitude. He continues to explain that dynamic properties such as time lag depend on the material layers, thickness and sequence with respect to the direction of heat flow, and recommends that thermal mass be located inside the envelope insulation [2], the same location recommended by Givoni [3]. In the context of hot climates, the Sustainable Energy Authority of Victoria states that thermal mass added within the insulated building envelope helps reduce extreme temperature fluctuations and moderates internal temperatures with direct benefits to occupant comfort [4].

HVAC systems and thermal mass

The Sustainable Energy Authority of Victoria describes thermal mass in cooling applications as a heat sink, absorbing heat gains in the space and reducing or delaying the need of supplementary cooling. It recommends that the stored heat be extracted at night with natural ventilation or by exhaust fans (nocturnal pre-cooling), and though night indoor temperatures will be higher than if there were low thermal mass, they will remain within the comfort range [4].

Easton also cautions that evening temperatures will be warmer in a heavy mass building than in a lightweight one; however he adds that even if mechanical cooling is required to extract excess heat, the equipment can be run at night when lower outdoor temperatures enable the equipment to operate with higher efficiency. Therefore, the space cooling load shift can reduce the energy demand during peak hours and improve operating efficiency [6].

The effect of thermal mass on space temperatures and HVAC system performance is recognized by ASHRAE in the ASHRAE Handbook: HVAC Applications. Citing that both peak heating and cooling loads can be reduced through effective use of building thermal storage, the building storage section also cautions that although equipment sizes can be reduced their operating periods may be increased and in some cases result in increased energy use [7].

Simmonds describes his design methodology for a building located in The Netherlands, with peak design conditions similar to those in Vancouver, Canada. The building incorporated 200 mm concrete floor slabs and 200 mm concrete external walls and the design successfully eliminated the need for a cooling plant [8].

According to several sources, benefits of using thermally massive construction are most pronounced for locations with a big difference between the maximum day temperature and minimum night temperature. Szokolay suggests that a mean range (12 month average of the mean maximum and minimum temperatures) of 8 ºC warrants heavy mass construction

[2]. When applying nocturnal cooling, the diurnal temperature range recommended by Givoni is 12 ºC to 15 ºC with minimum nighttime temperatures below 20 ºC [3].

Estimated percentage savings in heating and cooling energy consumption are in range of 6% to 25% [1, 4].

The available resources indicate that there is a potential for reducing the energy use and peak load demand of a building with properly designed thermal mass and optimum system control of solar loads and mechanical HVAC systems. The research suggests that the magnitude of savings is dependent on climate and that locations with wide daily temperatures ranges will benefit most.

Energy simulations

Mechanical systems are not assumed or simulated and the results will not represent the total building energy consumption required to operate the mechanical systems. To calculate this total energy use would require many assumptions regarding mechanical system type and configuration, heating and cooling plant energy conversion efficiencies, distribution system losses, lighting power, and service water heating. Even though the selected simulation software is capable to simulate all those building systems parameters, this analysis strategy was selected to isolate the passive effect of thermal mass from system type and performance assumptions, and to enable the results to be applied to a variety of system types.

Simulation parameters: fixed parameters

The following fixed building parameters were implemented in all simulation models:

– location – Belgrade, Serbia,
– building type – office building,
– shape – rectangular floor plan,
– height – 4 stories with 3.7 m per story,
– floor area – 25 m × 39 m per floor, total 3,900 m^2,
– glazing to wall area: 36%,
– operations – 9:00 to 17:00,
– occupant density – 7 people/100 m^2,
– occupant sensible heat gain – 5 W/m^2,
– equipment sensible heat gain – 8 W/m^2,
– lighting heat gain – 11 W/m^2, and
– ventilation rate – 10 L/s per person.

Table 1. Belgrade – external wall thermal properties

Description	U value [Wm^{-2} ºC^{-1}]
Roof	0.505
External wall	0.870
Slab on grade	1.093
Glazing	3.299

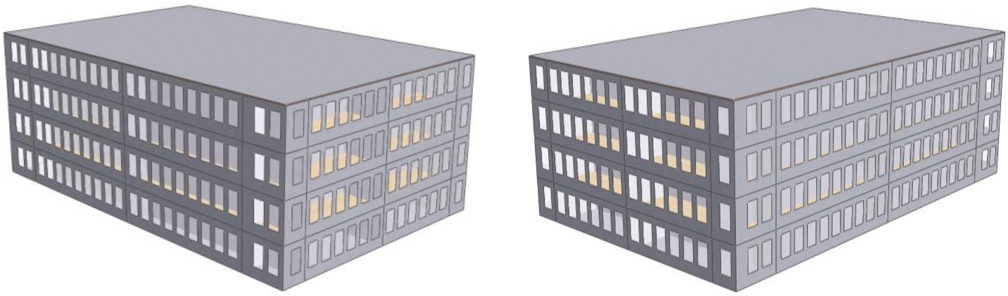
The maximum heat transfer coefficients – U values were used in building envelope simulation (tab. 1).

Simulation parameters: variable parameters

The following variables were simulated in all possible combinations:

– dominant Mode of Heat Transfer:
– convective; 100% convection – representing space temperature control by forced-air heating and cooling and,
– radiant; 50% radiation, 50% convection – representing space temperature control by low-intensity radiant heating and cooling,

– building orientation: two building orientations were simulated for each dominant mode of heat transfer.



(a) **(b)**

Figure 1. Building orientations; (a) Long axis aligned east-west, (b) Long axis aligned north-south

Simulation parameters: concrete thickness and U-value

In each case, the simulated building envelope insulation thickness remained constant and only the concrete thickness and its location within the building element were changed. The resulting building element assemblies have slightly different U-values. This approach reflects typical wall insulation specifications, which are usually based on nominal insulation R-values. Also, the cases that have batt insulation on the internal side of the concrete contain a 13 mm layer of drywall, which does not exist on the other external wall cases. The cases with dominant convective heat transfer were simulated with false ceiling, while the cases with dominant radiant heat transfer were modeled with exposed concrete ceiling surface.

The effect of the mass on the external wall assembly U-values for the three massing cases applied to the simulated office building in Belgrade are shown in tab. 2.

Table 2. Belgrade – External wall thermal properties

Description	U-value [$Wm^{-2}\,^{o}C^{-1}$]
Lightweight steel frame, batt insulation with continuous insulation (benchmark case)	0.870
Medium amount of concrete with batt insulation on the interior side of the concrete	0.806
Medium amount of concrete with batt insulation on the exterior side of the concrete	0.834
Heavy amount of concrete with batt insulation on the interior side of the concrete	0.762
Heavy amount of concrete with batt insulation on the exterior side of the concrete	0.787

Simulation parameters: concrete thickness and distribution

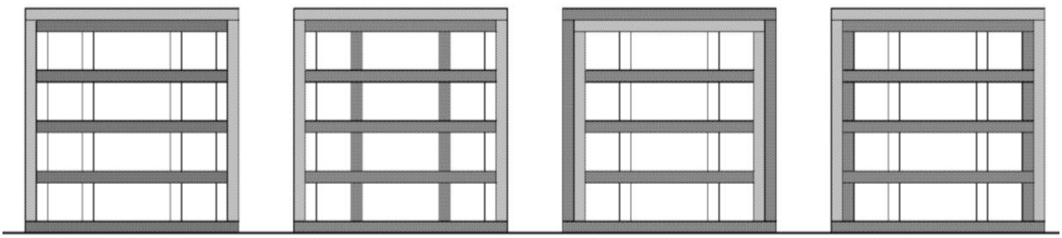
Table 3 gives parameters used for simulation and fig. 2 presents concrete mass distribution.

Simulation parameters: weather file

Energy Plus weather file (SRB_Belgrade.132720_IWEC.epw file) was used for dynamic thermal simulation of the office building in Belgrade. This weather file is publicly available and a good source is the U.S. Department of Energy.

Table 3. Simulation parameters, concrete thickness

Case	Description	Concrete thickness [mm]			Overall building concrete density	Net storage capacity
		External wall	Floor / Ceiling	Interior wall	[kg m^{-3} building]	[kWh°C^{-1}]
Low mass	Concrete is used in the floors and ceiling only.	0	50	0	24	90
Medium mass, interior walls	Concrete is used in the floors, interior walls, and interior side of roof structure.	0	100	50	100	493
Medium mass, envelope exterior	Concrete is used in the floors, external walls and roof located on the exterior side of insulation.	100	100	0		
Medium mass, envelope interior	Concrete is used in the floors, external walls and roof located on the interior side of insulation.	100	100	0		
Heavy mass, interior walls	Concrete is used in the floors, interior walls, and interior side of roof structure.	0	200	100	200	986
Heavy mass, envelope exterior	Concrete is used in the floors, external walls and roof located on the exterior side of insulation.	200	200	0		
Heavy mass, envelope interior	Concrete is used in the floors, external walls and roof located on the interior side of insulation.	200	200	0		



(a) (b) (c) (d)

Figure 2. Concrete mass distribution; (a) low mass, (b) interior walls, (c) envelope exterior, (d) envelope interior, concrete, insulation, no mass

Simulation results

The following tables and graphs present simulation results for an office building in Belgrade for all massing cases, for one building orientation (longer axis aligned east-west), for both dominant building heat transfer modes: annual space heating and cooling energy

Table 4. Building massing cases

ID	Description
1	Low mass (benchmark)
2	Medium mass – Interior walls
3	Medium mass – Envelope exterior
4	Medium mass – Envelope interior
5	Heavy mass – Interior walls
6	Heavy mass – Envelope exterior
7	Heavy mass – Envelope interior

consumptions and peak space heating and cooling demands. For simplicity, only the results for the building aligned with the long axis in the east-west direction were displayed. This was because the simulation results for the building aligned with the long axis in the north-south direction showed similar trends in response to increasing thermal mass. In all tables low-mass building was used as benchmark case.

Table 4 contains an overview of simulated building massing cases.

Table 5. Annual space heating and cooling energy consumption for the building oriented with long axis aligned east to west – convective heat transfer

Building massing case ID	Convective heat transfer							
	Space heating energy			Space cooling energy			Net savings	
	Required	Savings		Required	Savings			
	kWh/m^2 per year	kWh/m^2 per year	%	kWh/m^2 per year	kWh/m^2 per year	%	kWh/m^2 per year	% of total H + C
1	80.7	–	–	48.54	–	–	–	–
2	79.88	0.82	1%	45.58	2.96	6%	3.78	3%
3	63.45	17.25	21%	48.82	-0.28	-1%	16.97	13%
4	63.59	17.11	21%	48.49	0.05	0%	17.16	13%
5	79.06	1.64	2%	44.98	3.56	7%	5.2	4%
6	61.7	19	24%	48.86	-0.32	-1%	18.68	14%
7	61.84	18.86	23%	48.44	0.1	0%	18.96	15%

Table 6. Annual space heating and cooling energy consumption for the building oriented with long axis aligned east to west – radiant heat transfer

Building massing case ID	Radiant heat transfer							
	Space heating energy			Space cooling energy			Net savings	
	Required	Savings		Required	Savings			
	kWh/m^2 per year	kWh/m^2 per year	%	kWh/m^2 per year	kWh/m^2 per year	%	kWh/m^2 per year	% of total H + C
1	63.8	–	–	36.8	–	–	–	–
2	63.16	0.64	1%	33.19	3.61	10%	4.25	4%
3	49.77	14.03	22%	36.78	0.02	0%	14.05	14%
4	49.82	13.98	22%	36.51	0.29	1%	14.27	14%
5	62.42	1.38	2%	32.61	4.19	11%	5.57	6%
6	48.18	15.62	24%	36.79	0.01	0%	15.63	16%
7	48.25	15.55	24%	36.38	0.42	1%	15.97	16%

Discussion of simulation results

In general, the simulation results indicate space heating and cooling energy requirements and peak space heating and cooling demand reductions when thermal mass is added to the building envelope and structure. The savings are measured for each case against the benchmark case with the same building orientation and dominant mode of heat transfer. 28 simulations were conducted in total, and 4 of those were benchmark cases. The simulation data showed that in comparison with the respective benchmark cases:

- 100% of all simulated cases experienced reduced annual space heating energy requirements,
- 67% of all simulated cases experienced reduced annual space cooling energy requirements,
- 83% of all simulated cases experienced reduced peak space heating demand, and
- 50% of all simulated cases experienced reduced peak space cooling demand.

Table 7. Peak space heating and cooling demands for the building oriented with long axis aligned east to west – convective heat transfer

Building massing case ID	Convective heat transfer					
	Peak space heating demand			Peak space cooling demand		
	Required	Demand reduction		Required	Demand reduction	
	[Wm^{-2}]	[Wm^{-2}]	[%]	[Wm^{-2}]	[Wm^{-2}]	[%]
1	118.07	–	–	85.32	–	–
2	119.75	–1.68	–1%	88.17	–2.85	–3%
3	105.72	12.35	10%	86.05	–0.73	–1%
4	104.3	13.77	12%	86.04	–0.72	–1%
5	114.76	3.31	3%	88.12	–2.8	–3%
6	102.5	15.57	13%	82.48	2.84	3%
7	101.03	17.04	14%	83.01	2.31	3%

Table 8. Peak space heating and cooling demands for the building oriented with long axis aligned east to west – radiant heat transfer

Building massing case ID	Radiant heat transfer					
	Peak space heating demand			Peak space cooling demand		
	Required	Demand reduction		Required	Demand reduction	
	[Wm^{-2}]	[Wm^{-2}]	[%]	[Wm^{-2}]	[Wm^{-2}]	[%]
1	121.41	–	–	75.5	–	–
2	122.2	–0.79	–1%	76.1	–0.6	–1%
3	106.47	14.94	12%	72.58	2.92	4%
4	105.88	15.53	13%	73.42	2.08	3%
5	115.03	6.38	5%	76.88	–1.38	–2%
6	100.07	21.34	18%	73.14	2.36	3%
7	99.24	22.17	18%	73.3	2.2	3%

Discussion: thermal mass and peak space heating and cooling demands

Most of the simulation results indicated that both the peak space heating and cooling demand can be suppressed by adding effectively integrated thermal mass. As an example, 24 hours heating and cooling load profiles were extracted from simulation data and shown in figs. 3 and 4.

The load profiles are for identical top floor south-east corner office zones in two identical buildings in Belgrade; one has a lightweight envelope (benchmark case) and the other has a heavy mass envelope (case with mass on the inside of the envelope insulation). In heating mode, the heavy mass elements absorb heat from the Sun and internal sources such as lights and occupants during the day. This heat is stored and gradually released during the nighttime thereby reducing the peak heating load, which typically happens during the early morning hours. In cooling mode, the heat gains in the space are absorbed by the massive elements before they affect the space temperature requiring less space cooling demand from the mechanical system to maintain the space temperature set point.

The space heating and cooling demand profiles in the figures above indicate the peak heating demand of 1.5 kW for the lightweight building was reduced to 1.1 kW with the addition of thermal mass and the peak cooling demand was reduced from 1.9 kW to 1.7 kW with the addition of thermal mass.

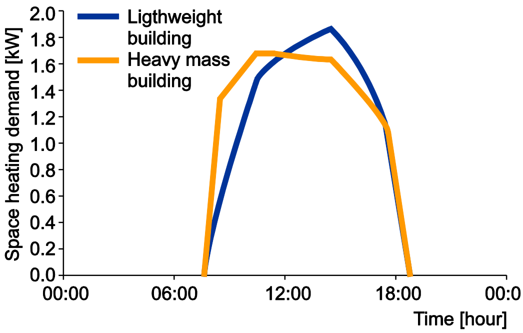


Figure 3. 24 hours space heating demand profile

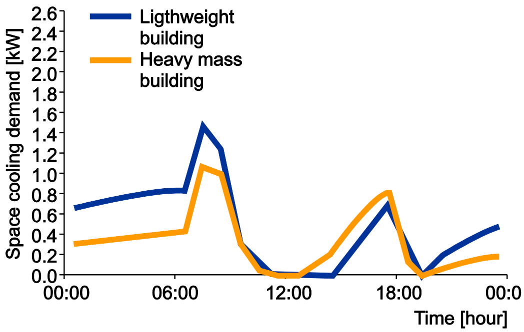


Figure 4. 24 hours space cooling demand profile

Discussion: thermal mass and annual space heating and cooling energy requirements

All the simulations indicated that the annual space heating energy requirement was lowered with increasing amounts of thermal mass in the building envelope and structure. The results also indicated that the medium and heavy mass buildings experience lower peak space heating demands and/or less extreme fluctuations in demand than the lightweight building.

All of the simulations indicated a decrease or a negligible increase in the annual space cooling energy requirement with the similar trend with the peak space cooling demand. The space cooling energy requirement results from the amount of solar radiation stored during the day and its gradual build up over time. The amount of stored heat is a function of the available solar radiation and daily outdoor temperature range in different climates; however a detailed investigation of these parameters is outside the scope of this study.

For simple and consistent case comparisons, the space temperature control strategy in the simulations was not varied or optimized for night pre-cooling. Several ASHRAE studies on real and experimental buildings found that cooling energy savings could be achieved using building thermal mass but require an optimized system control strategy tailored to the building and location [9].

Discussion: mass thickness

Most of the simulation results indicated that increasing thickness of the thermal mass reduced the annual space heating energy requirement and the peak space heating and cooling demand.

The effect of further increasing the thickness of the thermal mass, beyond the 200 mm wall thickness of the heavy mass cases, was outside the scope of this study. Within the parameters of this study, most cases experienced improved energy performance with the heavy mass construction, however, there was no indication that further increasing the thickness was beneficial. Simmonds investigated slab thicknesses of 200 mm and greater and found that the increased thickness did not provide improved thermal capacitance [8]. Santa Monica Green Building Program suggests that there is little benefit beyond 100 mm slab thickness [10].

Discussion: mass location

The simulation results indicated a relationship between the location of the thermal mass within the building elements and the reduction of annual space heating and cooling energy requirements of the building. In the simulations the thermal mass was distributed evenly throughout the building. However, concentrating the thermal mass on a specific exposure (as is done with many passive solar designs) may yield different results. Testing various applications of this strategy is outside the scope of this study.

Thermal mass on the exterior side of the envelope insulation will result in more stable exterior surface temperatures, slowing the rate of heat gain/loss in the occupied space. All simulated cases with this mass location indicated reduced annual space heating energy requirements and 66% cases reduction of annual space cooling energy requirements. During the winter, solar heat stored in the mass will be released back to the outside during the nighttime. This keeps the outer layer of the envelope warmer for longer than a low mass wall, resulting in less heat loss from the building interior. When the same interaction occurs during the summer, however, the reduced rate of heat loss may be less favorable The simulation results confirmed this and indicated a negligible reduction of annual space cooling energy requirements. The benefit of thermal mass on the exterior surface in the summer is that the mass does not reach temperatures as high as lightweight materials, resulting in less conductive heat gain in the occupied space and, therefore, better occupants thermal comfort.

Thermal mass in the interior walls will absorb/emit radiant heat to/from the occupants and other exposed surfaces and will help to buffer the effects of internal heat gains and limit fluctuations in the internal temperature. Thermally massive floors help to buffer internal temperatures in the same way as internal walls; however, the opportunity for solar energy storage in floors is typically higher due to their orientation. For example, solar radiation entering through a window is absorbed by a massive floor before it affects the space. The temperature of the floor slowly rises, and the heat is released only if the space temperature is lower than the surface temperature.

The simulation results indicated that increasing the thermal mass only in the interior walls results in much smaller reduction of annual space heating energy requirements than in cases with thermal mass located in the external walls. The results showed opposite trend with annual space cooling energy requirements. These results can be explained with heat storage properties of heavy mass external walls (they stay warmer for longer than a low mass external walls) and increased heat loss from the building interior in buildings with low mass external walls. The peak cooling demands in the cases with thermal mass in the internal walls and floors are in all cases higher from the peak cooling demands of the low mass buildings (benchmark cases). This indicates that massive internal building structure cools off slower during the night and, therefore, the mechanical cooling system needs to work harder in the morning of the new working day.

Regardless of the energy performance, the location of thermal mass affects occupant comfort and the time lag between fluctuating outdoor conditions and the interior environment. Space resultant temperature is one of the parameters that define occupant thermal comfort. It is directly influenced by indoor air temperature and surrounding surface temperatures – mean radiant temperature. Thermal mass in the interior walls (isolated from fluctuating outdoor conditions) will absorb/emit radiant heat to/from the occupants and other exposed surfaces and will help to buffer the effects of internal heat gains and limit fluctuations in the internal temperature. With thermal mass located on internal side of envelope insulation, interior surface temperatures are more stable than in case of the space with lightweight envelope. Therefore, it can be concluded that thermal comfort and HVAC systems operation is more stable in heavy mass buildings due to less internal surfaces temperature fluctuations. Detailed analysis of interior surface temperatures and occupant thermal comfort is outside the scope of this study.

Discussion: convective vs. radiant heat transfer

The simulation results indicated that the differences in space heating and cooling energy requirements and peak space heating and cooling demands between the convective and radiant heat transfer cases were more significant than between different levels of thermal mass. The contribution of a controlled radiant surface to the space resultant temperature allows for a wider tolerance of air temperatures while maintaining comfortable conditions. The wider tolerance of air temperatures in combination with thermal storage capacity of the mass results in lower space conditioning requirements than with convection systems.

Discussion: building orientation

Two building orientations were simulated for the rectangular building in each combination of dominant mode of heat transfer and massing cases. For simplicity, only the results for the building aligned with the long axis in the east-west direction were displayed. This was done because the simulation results for the building aligned with the long axis in the north-south direction showed similar trends in response to increasing thermal mass.

There were differences between the north south long energy results and the east west long energy results, for the building with the same massing combination. In general, the space heating and cooling energy results were inversely affected; when the space heating energy requirement was increased the space cooling energy requirement was decreased. The difference was never greater than 20% of the annual space heating and cooling energy requirement, and in most cases it was between 4% and 15%.

Conclusions

This parametric study was conducted to investigate the relationship between increasing the amount of thermal mass (concrete) in a building and its energy performance. The study was focused on passive building energy performance and compared annual space heating and cooling energy requirements for a building with several different applications of thermal mass.

The simulation results demonstrated that there exists a potential for reducing space heating and cooling energy requirements with heavy mass construction in analyzed climate region (Belgrade, Serbia). Since the primary energy consumption of the mechanical HVAC system is a function of the space heating and cooling energy requirement, a system that can provide energy output that tracks the thermal load of a building will consume less primary energy in a heavy mass building than in a lightweight one.

The simulations showed that peak space heating and cooling demands were also reduced when thermal mass was added to the building. The building HVAC system capacity is sized to meet peak space heating and cooling demands; therefore, reducing the peak demand allows the mechanical HVAC system capacity to be downsized. Small capacity HVAC equipment can be selected to operate with high efficiency under steady operation. This combination not only reduces the annual energy consumption of a building, it combines well with many renewable energy sources.

The simulations demonstrated that the addition of thermal mass had a greater effect on the space heating and cooling energy requirements in buildings conditioned by radiation than those conditioned by convection. This showed that radiant heat transfer plays an important role in the behavior of thermal mass. Therefore, it is important to consider radiant heat transfer when designing heavy mass buildings regardless of their mechanical HVAC systems.

Peak space heating and cooling demands were lower in cases having thermal mass on the interior side of the envelope insulation. Therefore, HVAC system response is affected by the location of thermal mass.

To effectively reduce total building energy consumption requires a primary focus on the building itself, with design teams working together to incorporate passive energy efficiency features prior to considering the HVAC mechanical equipment. The main priority in high performance building design should be always to reduce building heating and cooling energy requirements as much as possible before HVAC system selection and sizing. The application of mass for the purpose of energy conservation requires careful design and consideration of building and climate specifics, and energy simulation tools can be quite helpful. Because of the relationship between the passive design features and the building architecture, the best opportunity to apply thermal mass effectively is during the early design phase. Thermal storage with building mass is one passive feature that can be incorporated with the building architecture to reduce the energy use of building while maintaining occupant comfort.

References

[1] ***, University of Maryland, 2005; Solar Decathlon Team. Thermal Mass. 2005, http://2005.solarteam.org/page.php?id=223
[2] Szokolay, S. V., Dynamic Response of Buildings, in: Introduction to Architectural Science – The Basis of Sustainable Design, Architectural Press/Elsevier, Burlington, Mass, USA, 2004, pp. 45-49
[3] Baruch, Givoni, Minimizing Cooling Needs By Building Design, in: Passive and Low Energy Cooling for Buildings (Givoni, B.), John Wiley & Sons, Inc., New York 1994, pp. 21-34
[4] ***, Sustainable Energy Authority Victoria. Thermal Mass Info Fact Sheet, 2004, pp. 1-6 http://www.sustainability.vic.gov.au/resources/documents/Thermal_mass.pdf
[5] ***, Chapter 35, Sustainability, in: 2009 ASHRAE Fundamentals Handbook, pp. 35.6-35.8
[6] Easton, D., Mass Walls Mean Thermal Comfort, Home Energy Magazine Online May/June 1999, p. 37
[7] ***, Chapter 34, Thermal Storage, in: 2003 ASHRAE Applications Handbook, pp. 34.1-34.2
[8] Simmonds, P., The Utilization and Optimization of a Building Thermal Inertia in Minimizing the Overall Energy Use, ASHRAE Transactions 1991, pp. 1031-1042
[9] Braun, J. E., Reducing Energy Costs and Peak Electrical Demand through Optimal Control of Building Thermal Storage, ASHRAE Transaction 1990, pp. 876-888
[10] ***, City of Santa Monica. Santa Monica Green Building Program. Thermal Mass. 2010, http://www.smgov.net/Departments/OSE/Categories/Green_Building/Guidelines/Envelope_+_Space_Planning/Thermal_Mass.aspx.

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