Leadership in Sustainable Infrastructure
*Leadership en Infrastructures Durables*

Vancouver, Canada
May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

# DESIGNING BUILDINGS FOR POST-DISASTER RESILIENCE WITH THERMO-ACTIVE RADIANT AIR CONDITIONING SYSTEMS

Laken, Jack[1], Burak, Robert[2]
[1] Termobuild, Canada
[2] Canadian Precast/Prestressed Concrete Institute. Canada

**Abstract:** Climate change is a reality in today's world. We are experiencing an increase in frequency and intensity of extreme weather conditions - heavier rainfall, draught, extreme heat and cold as well as unique events such as ice storms and floods. With these events, governments, cities and even insurance companies are seeing significant impacts on the built environment, particularly buildings. ''Extreme weather has the ability to affect short and long-term macroeconomic statistics, as evidenced: it can add or subtract 110,000 jobs from monthly North American employment - It is now the single most-watched economic statistic in the world, and generally thought to be one of the most accurate" Kenneth Rogoff, Professor of Economics and Public Policy at Harvard University. Agencies and businesses need strategies to cope with these (now) more common extreme events. One often overlooked functional attribute of a building is the ability to provide a level of habitation and operability after an extreme weather event that will allow businesses and people to continue to function without loss of employment. This paper discusses a technology that enables a building to have 'business as usual' operation in cases where extreme weather events can result in significant long term power outages. Specific to resilient design and healthy buildings is the philosophy of thermal storage using thermo-active, hollowcore precast radiant air conditioning systems that ensure a building will maintain air quality and temperature and continue to be habitable during and after extreme weather events - A post-disaster resilience strategy in the age of climate change that ensures economic viability of businesses and cities.

## 1 INTRODUCTION

"Building resiliency is the capacity of a building to continue to function and operate under extreme conditions, such as (but not limited to) extreme temperatures, sea level rise, natural disasters, etc. As the built environment faces the impending effects of global climate change, building owners, designers, and builders can design facilities to optimize building resiliency." (Whole Building Design Guide 2016). The above quote indicates a trend that is driven by the growing understanding by governments, organizations, and design professionals that are seeking ways to better address climate change and the conservation of our natural environment. The link between resiliency and sustainability is becoming more apparent to all concerned.

Planning and having a business continuity plan in place to cope with any type of disruption makes good business sense - so does understanding the risks that could leave property and operations vulnerable in the event of natural disasters, power outages, or indoor comfort system failures as it relates to resilience. What business functions or assets, if interrupted or lost in an extreme event, could impact the ability to provide goods and services? Identifying critical functions of processes and resources vital to the continuity of a business or a neighbourhood will lead to a prevention and mitigation plan to leverage existing resources.

To achieve resilience, buildings need to be designed to safeguard health and comfort and sustain process for the future in the adverse events due to climatic conditions. Designing to current standards may not be enough to combat the effects of climate change.

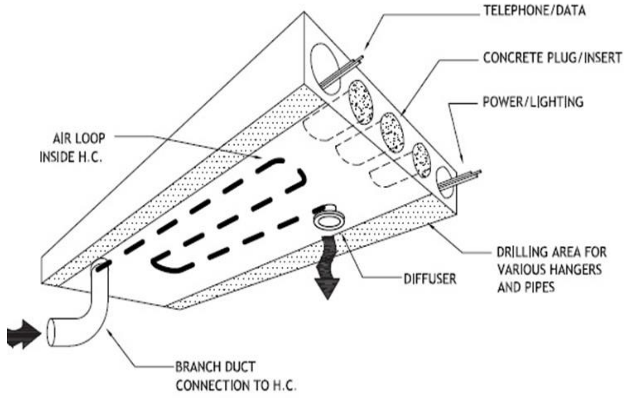
Mass buildings such as those designed with concrete, provide good thermal stability, a robust and environmentally friendly solution to the need for resilience - reducing, or in many cases eliminating, the need for mechanical cooling. Research has shown that buildings with high levels of thermal mass, passive solar features and effective ventilation control perform extremely well (Arup & Bill Dunster Architects, 2004). This approach to design is a strategy to future-proof new buildings – providing comfortable living now, and in the future.

## 2 FACTORING IN RESILIENT MATERIALS – HOLLOWCORE PRECAST CONCRETE FLOOR AND ROOF SLABS

The high level of thermal mass provided by concrete is playing an increasingly important role in ensuring comfortable internal conditions in commercial and institutional buildings as well as providing an additional benefit - resiliency. The use of concrete opens the potential of low-energy design as the building fabric and the way in which it interacts with the internal and external environment can be exploited for: 1. thermal energy storage in both heating and cooling seasons, 2. demand reduction, and 3. resiliency of the buildings.

According to Navigant Research "the global energy storage industry reached significant milestones in 2015, and momentum is expected to continue through 2016 and beyond. Rapidly falling technology costs and innovative new business models are combining with government policies and regulatory reforms to enable a dynamic and fast growing market for energy storage". The use of concrete as a thermal storage medium allows passive cooling and heating when actively engaged. The active engagement of the concrete in thermal dynamics of the building system is best achieved by using hollowcore precast prestressed concrete planks (slabs) as a medium of distribution of air through their cores and thereby working as a thermal storage medium. Pairing it to work as ventilated ceiling (See Figure 1), and considering the reduction in greenhouse gas emissions enables significant environmental and cost savings of a building over its life through reduced energy use. From a broader sustainability perspective, it is important to consider the impact of climate change on the internal environment; the use of thermal mass is a key adaptation measure for mitigating the impact of rising temperatures and unstable weather patterns resulting from climate change.

Hollowcore precast concrete slabs are already commonly used as the floors and roofs for the construction of commercial, institutional and industrial building as well as residential buildings spanning from office buildings, educational building, condos, medical facilities, warehouses and others. Pairing them in a thermo-active ventilation system becomes a natural progression and extension of the already established construction technology.




**Cooling Capacity of the Basic System**

– 40W/m² or 12.68 Btu/hr/sq.ft
– 50W/m² or 15.86 Btu/hr/sq.ft
(with supplementary cooling) or
– 60W/m² 19.02 Btu/hr/sq.ft (with supplementary cooling + direct boost).

Figure 1: Pairing Ventilation with Hollow Core Slabs – Cooling Capacity; A temperature differential of 30 Deg F or +15 Deg.C can be observed in hollow core slabs between input temperature and output at the air diffuser during a typical night time charging cycle. This differential reveals great energy storage capacity to maintain comfort in a large variety of buildings.

## 3 THERMAL DYNAMICS OF BUILDING MASS AND RADIANT AIR CONDITIONING SYSTEMS

The volumetric thermal capacity of concrete with a density of 2300 kg/m$^3$ is 2.07MJ/m$^3$ per $^o$K. This can be translated to say that to raise the temperature of 1 m$^3$ concrete to 1°K requires approximately 575 W-h. However, this can only be of value if, first, a substantial amount of this mass is available for the storage of thermal energy, and second, some control over the heat to and from the concrete can be exercised. The heat capacity of commonly used precast hollowcore slabs is estimated on a per square meter basis to be about 100 W-h /m$^2$ per °K. Conventionally the thermal exchange between the room air and its walls and radiation exchange has a heat transfer value only in the order of about 10 W /m$^2$ per °K.

Concrete's ability to absorb heat and provide a cooling effect comes from the difference between the surface temperature and that of the internal air and other surfaces. Consequently, the greatest cooling capacity is provided when the internal temperature peaks. Therefore, to some extent a variable internal temperature is a prerequisite for buildings having heavy thermally active mass. However, to maintain comfortable conditions and limit overheating, peak temperatures should not exceed designed operative temperature for more than around 1% of the occupied period.

Operative temperature, also known as 'dry resultant temperature', is an important measure in such buildings. It considers radiant and air temperature, providing a more accurate indication of comfort than air temperature alone.

The relatively stable radiant temperature provided by the thermal mass in concrete is a significant factor in maintaining comfortable conditions. It enables higher air temperatures to be tolerated than in lighter-weight buildings, which are subject to higher radiant temperatures resulting from warmer internal surfaces. Figure 2 shows a typical representation of the stabilizing effect of the thermal mass on internal temperature.

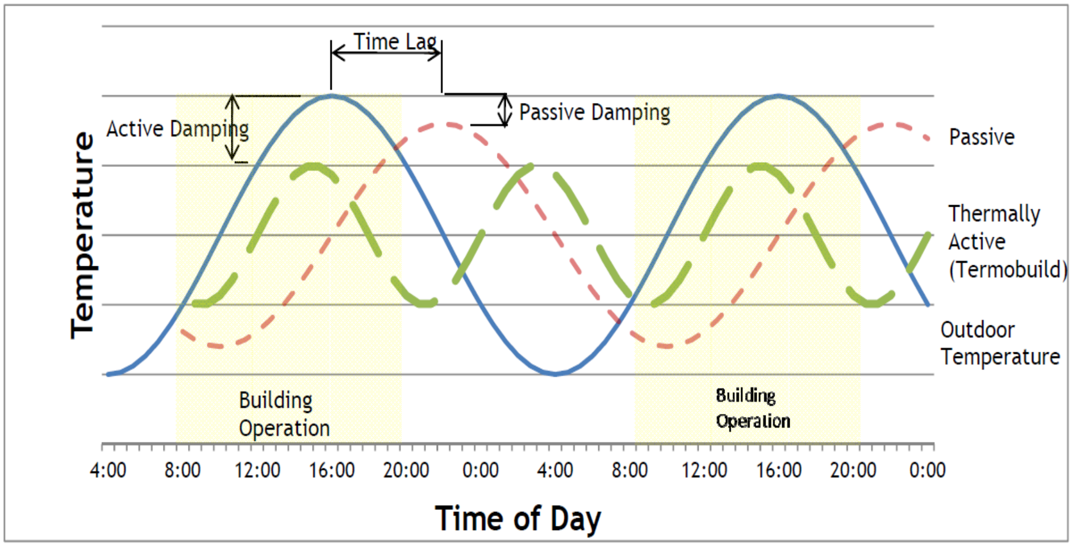



Figure 2: Stabilizing effect of thermal mass on internal temperature

When thermal mass of the buildings is actively engaged for energy transfer, the stored heat in the building mass from occupants and lights etc. can be used to compensate for night losses in winter. In summer the cool night air, when 10-15°C, can be circulated through the cores of the hollowcore slabs, which in turn are cooled to absorb the next day's heat gains without the need of refrigeration (See Figure 3). In places where the night is not cool enough (as in some parts of the USA and Canada) off-peak refrigeration would be required to pre-cool the buildings, but the concrete with its energy storage capacity can still handle the daytime loads. Passing air through the cores results in approximately doubling the heat transfer area. Moreover, the convective heat transfer is increased due to forced convection in the cores of the slabs. Due to the effectiveness of coupling of the supply air and mass, the temperature of the air leaving the slab is almost independent of the temperature entering the slab. On average about 75% of the thermal energy available from the tempered ventilation air can be absorbed by the slab. Consequently, using floors and ceilings as active thermal mass is less expensive when compared to the cost of conventional mechanical systems and provides the needful resiliency in operation which is not available with conventional mechanical systems.

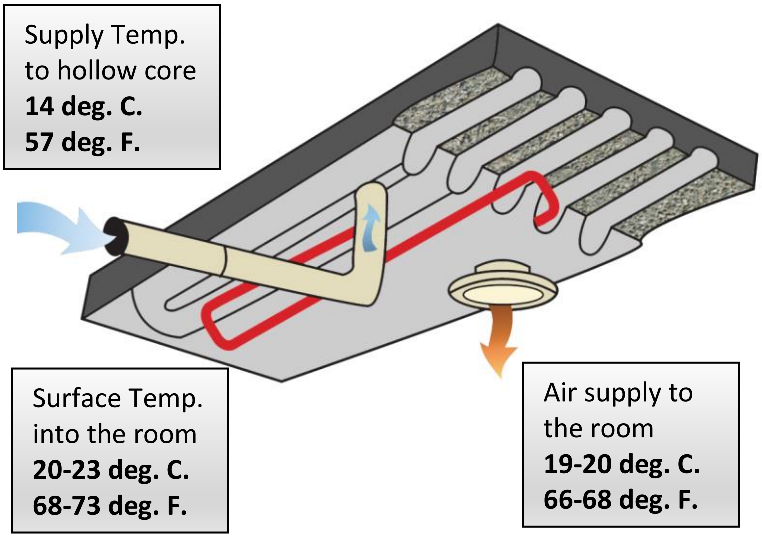



Figure 3: In the summer, cool night time air is absorbed in the hollow core concrete for dynamic release during the following day

The basic systems shown in Figures 1 and 3 can move an inert floor or roof from an idle state to intelligent state to capture, store and release low-grade energy upon demand. This reduces and/or eliminates the need for heating and cooling from nonrenewable sources and spreads the release of energy over a longer period. In the case of a power failure or other climate-change related events as they continue to release stored energy they ensure that the building is habitable providing a sustainable operation solution (Figure 4).

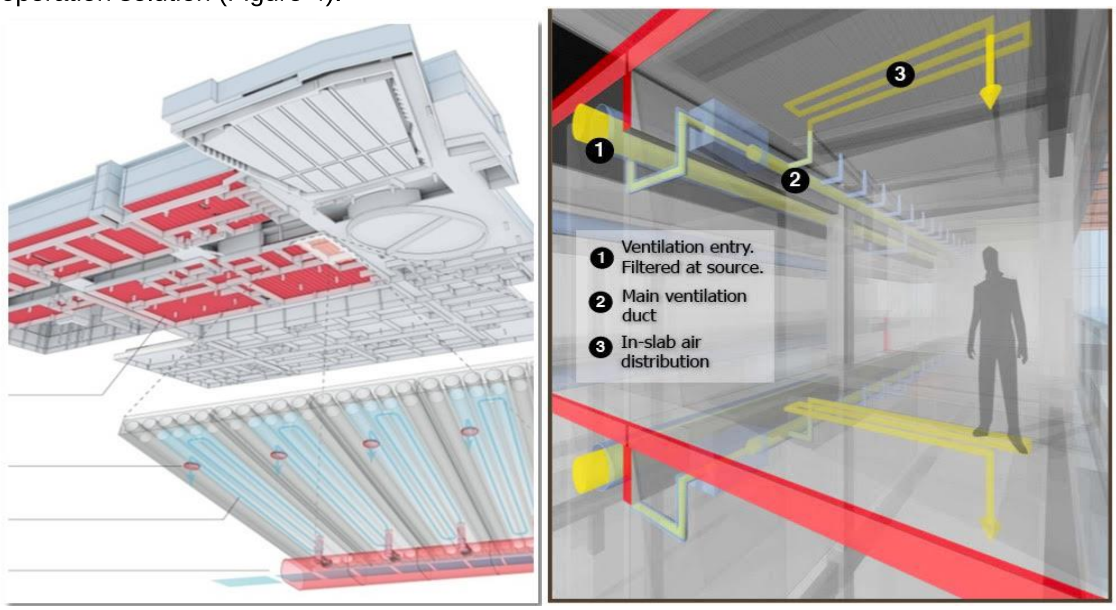



Figure 4: During normal operation, heating or cooling can be introduced from either ceiling or as displacement ventilation at floor level. During disruptive events stored energy continues to provide habitable spaces for a longer time (Images courtesy of B+H Architects)

The system is guided through intelligent software which empowers users to better manage comfort, resilience and energy inside of the buildings while reducing peak power consumption stress on the energy grid. By dialing-back the demand to the source it assists with the existing loads on the power grid supply capacity. When existing HVAC technologies are integrated with hollowcore slabs and thermal mass principles, the need for larger and more costly equipment is thereby reduced by up to 45% to 50%. The result of such integrated design eliminates the need for prefabricated ceiling panels, chilled beams, pipes or tubes that are common in typical ‘wet systems’. Unlike ‘wet systems’ that are can be costly and do not guarantee comfort due to their lack of integration with other building elements in the structure, an integrated design can outperform not only in terms of overall comfort but in energy efficiency, resiliency and sustainability.

Radiant air conditioning systems with thermal storage work intuitively with fan assisted ventilation system that pushes treated fresh air through a series of main ducts fed into branch ducts formed within the hollow core slabs of ceilings or floors (See Figure 5). As air passes along the ducts the concrete warms or cools the fresh air before supplying it to the occupied space. With stricter energy consumption guidelines, carbon foot print reduction targets, energy storage, resilience, net-zero energy buildings and “Smart City” initiatives, improved energy infrastructure management initiatives are at the center of this new and emerging shift to form a valuable part in the strategic response to external change.

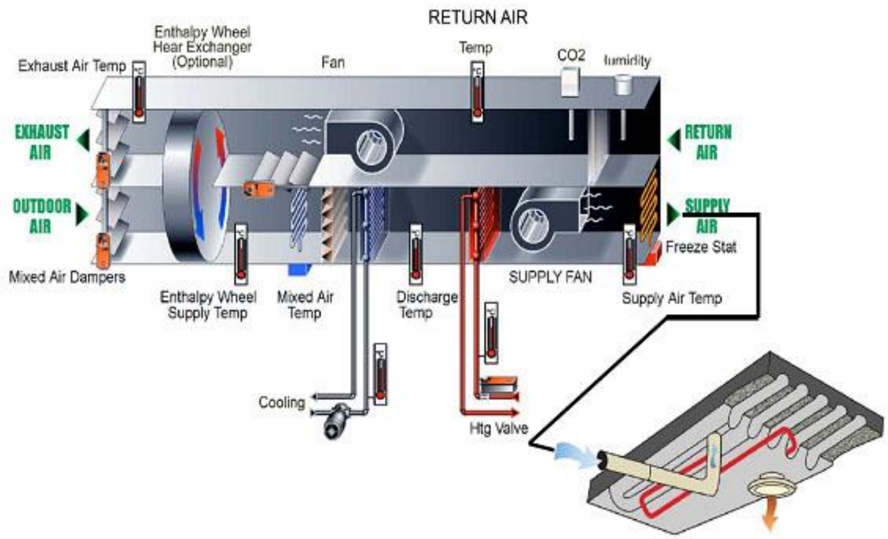



Figure 5: Radiant air conditioning systems with fan assisted ventilation trend

## 4 INSTITUTIONAL PROJECT PROFILES

The first system to integrate thermo-active radiant air conditioning systems in Canada was in 2006 at the Centre for Manufacturing and Design Technologies at Sheridan College's William G. Davis campus in Brampton, Ontario. The Centre houses teaching and lab rooms and a fully equipped advanced manufacturing lab that will use simulators and full-size robots to train students in the use of computerized manufacturing for careers in the auto industry and industrial design. In an interesting turn of events the building, after occupancy, was left without heating in an entire wing over the winter. In a typical HVAC building this would have closed the classrooms in an entire wing, but in this situation the thermo-active system could provide enough comfort to keep the wing open. The Chief Operating Engineer at Davis Campus commented as follows: “I was impressed with the new equipment in the c-wing building. Due to piping problems, we had almost no heating in that wing over the winter. However, with the new heat wheels and the hollow core slab system we were able to still able to keep the building at reasonable temperatures for classes. Compared to the old fan systems this is quite amazing.”

Another project, the LEED Gold Mundy’s Bay Elementary School in Midland Ontario (Figure 6), utilizes a radiant air conditioning system that was rated best performing by EnerLife Consulting out of more than 500 schools in Ontario in 2010-2011. Enerlife’s in-depth consumption evaluation for more than 500 schools has been brought to one common denominator by using heating degree days of YYZ Pearson Airport. This evaluation approach eliminates the need for two identical school to be constructed side by side in one location using two different heating/cooling systems, since educational buildings usually are built utilizing lean budgets and follow the same or similar School Construction Guidelines.

Figure 6: Mundy's Bay Elementary School – Inside classroom view of the hollow core radiant energy technology

Based on a gross floor area of 4,792 m², the annualized energy intensity for the Mundy's Bay Elementary school is 138 equivalent kWh² or 12.8ekWh/sq.ft. (See Figure 7).

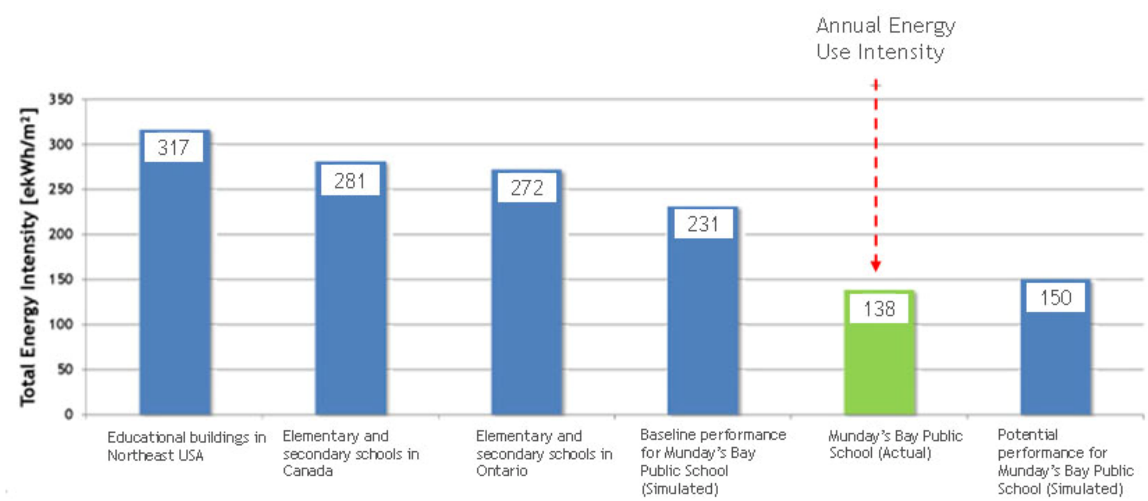
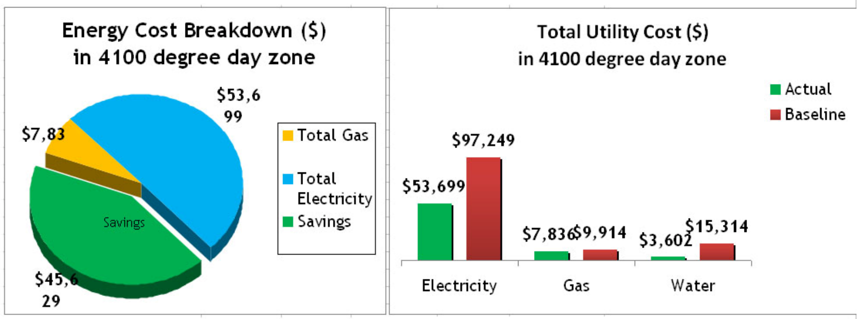



Figure 7: Energy intensity measured in ekWh/m² for various Educational Buildings

When compared to the potential performance obtained from the calibrated simulation, the Mundy's Bay Elementary School is performing better than predicted. Energy consumption data for entire facility was retrieved from utility invoices (gas and electrical) and analyzed for full 12 month (See Figure 8). The School's energy consumption* is comprised of electricity (lights, HVAC system, ground source heat pump and plug loads) and natural gas (boilers and domestic hot water). The utility costs averaged $0.10/kWh, gas was $0.54/ m³and water was $3.57/ m³.

| Savings Statistics | | | |
|---|---|---|---|
| Energy Cost Savings | 43% | Energy Savings | 40% |
| | $45,629 | | 445,827 ekWh |




| Utility Cost and Energy Intensity | | | | | | |
|---|---|---|---|---|---|---|
| | Actual Cost | | Baseline Cost | | Cost Savings | Energy Intensity |
| | [$] | [$/m²] | [$] | [$/m²] | [%] | |
| Water | $ 3,602 | $ 0.75 | $ 15,314 | $ 3.20 | 76% | 138 ekWh/m² or 12.8 ekWh/ft² |
| Electricity | $53,699 | $11.21 | $ 97,249 | $20.29 | 45% | |
| Gas | $ 7,836 | $ 1.64 | $ 9,914 | $ 2.07 | 21% | |
| Total utility | $65,136 | $13.59 | $122,478 | $25.56 | 47% | |

September 1, 2008 through November 30, 2008.

Figure 8: A summary of the actual energy consumption and utility cost savings for the Mundy's Bay Elementary School (2008)

In addition to providing the operational savings, the school has shown consistent maintenance of comfortable conditions with variable loads including the power outages, confirming the resiliency of the infrastructure.

Figure 2 demonstrated the stabilizing effect of thermal mass on internal temperature. Graphic validation of this is shown in Figure 9, below. Field data has been extracted from a Termobuild thermally charged educational building that was in an occupied mode. In this real-life situation the heating valve of a building was inadvertently closed for 11 hours during an occupied period in the winter when the outdoor temperatures ranges from -15.5ºC to -8.5ºC. The data shows that the indoor air remained in the comfort zone for the entire duration with no spikes, validating the resilience of the system during freezing outdoor temperatures. Conversely, the field data from a conventional building shows that the "ON-OFF" heating valve cycling during occupied hours is frequent to maintain the desired comfort to comply with ASHRAE fresh air ventilation recommendations, and to maintain comfort. Standalone conventional buildings are not suitable for "deep-energy-daily-cycling" (four or more hours) compared to thermally charged systems.


c

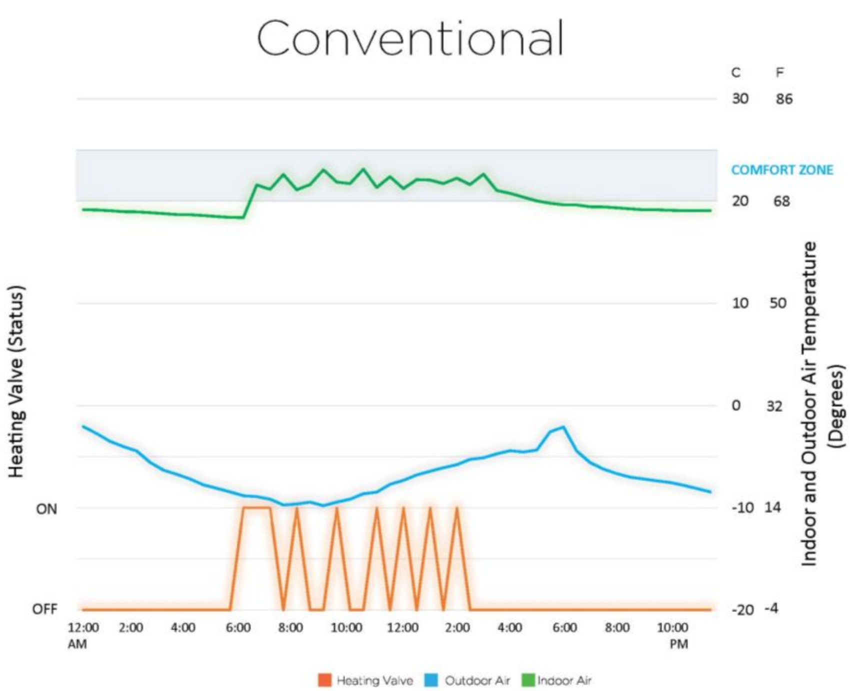



Figure 9: Trend logs related to resilience in thermally charged buildings. Field data trend logs are compared between a thermo-active hollowcore system (where the heating valve was inadvertently closed for 11 hours, and the building remained in an indoor comfort level) and a conventional system which requires frequent cycling to maintain indoor comfort.

## 5 Retrofit recommendations

Annually 1.7 million square metres of hollowcore slabs are manufactured in Canada and it is estimated that 50 million square metres have been installed in Canada since its first use in 1962. This represents a significant retrofit opportunity; retrofits where hollow core planks are found in existing buildings can instantly elevate a buildings performance, adding comfort and resilience along with energy efficiency while reducing environmental footprint. Where reductions in heating/cooling systems from 40% to 48% can be demonstrated, and with the addition of simplified controls, this type of retrofit is realistic. Evaluation of existing conditions can be carried out to establish meaningful recommendations on short and long term benefits using cost and payback as a reference.

## 6 CONCLUSIONS AND LESSONS LEARNED

This paper provided a brief introduction to a technology that enables a building to have 'business as usual' operation in cases where extreme weather events can result in significant long term power outages. Specific to resilient design and healthy buildings is the philosophy of thermal storage using thermo-active, hollowcore precast radiant air conditioning systems that ensure a building will maintain air quality and temperature and continue to be habitable during and after extreme weather events.

Essentially turning a buildings heating and cooling system into batteries, utilizing existing infrastructure, can reveal performance improvement opportunities aligned with latest trends, while providing a post-disaster resilience strategy in the age of climate change that ensures economic viability of businesses and cities.

Integration of hollowcore slabs with indoor comfort systems invites decision makers to shift the focus from individual non-integrated products to generic controls driven by thermo-active integrated systems that meet broader customer needs as they relate to: comfort and productivity, environmental footprint reduction, continuity of business functions, resilience, future-proofing real estate value, and non-utility financial benefits that exceed energy savings several times over.

## 7 REFERENCES

National Institute of Building Sciences. 2016.*Whole building Design Guide,* www.wbdg.org/

Arup & Bill Dunster Architects, 2004

Enerlife Consulting, 2011, *Top Energy Performing Schools Sustainable School Report* http://www.enerlife.com/

Navigant Research. https://www.navigantresearch.com/research/five-trends-for-energy-storage-in-2016-and-beyond