



INCREASING THE DURABILITY AND RESILIENCE OF TALL BUILDINGS WITH PRECAST CONCRETE ENCLOSURE SYSTEMS

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ABSTRACT

In this paper precast concrete wall systems are compared to curtain wall and window wall systems in terms of durability and disaster resilience of multi-story buildings. Window wall systems are currently the enclosure system of choice for tall residential buildings in most parts of North America.

Precast concrete wall systems can be expected to last the lifetime of a building with routine seal replacement. These are highly durable systems. Windows within precast concrete wall systems will require replacement in 25-35 years but represent a limited portion of the wall area and hence are less costly and have less impact on building use interruption.

The impact of façade choice on passive survivability and security are also considered. Maintaining livable temperatures in a space in Toronto, Ontario (a city with a climate similar to many Northern U.S. cities) during a power outage is shown to mostly depend on having little heat loss, reducing solar gains, and provision of thermal mass. A whole wall metric is also introduced which combines various vision and non-vision wall system heat loss components. A similar metric for solar gain is introduced. The most significant factor affecting this heat loss and solar gain (and thereby affecting thermal resilience) is to avoid high Window to Wall Ratios (WWR). This will apply for most wall systems but is most significant for systems like precast concrete where there is minimal thermal bridging through the insulation. In terms of security, precast concrete walls will protect occupants from projectiles and endure little damage during disasters. These impacts make precast concrete wall systems significantly more disaster resilient.

Keywords: Precast, Concrete, Durability, Disaster Resilience, Passive Survivability, Solar Gain, Heat Loss

1. INTRODUCTION

Buildings are products that provide spaces for human use and, in most cases, occupancy. The building enclosure is the element which physically separates these spaces from the outdoors. The enclosure has support, control, finish, and sometimes distribution (e.g. electrical, plumbing, etc.) functions. How and/or how well these functions are fulfilled directly affects in-service performance and other attributes of the building (beauty, sustainability, etc.). This paper will explore how precast concrete wall systems contribute to two important attributes, durability and resilience.

Precast concrete has been used successfully to provide durable building enclosures for many decades. As requirements for thermal performance, air leakage and rain penetration control increase in modern buildings, designers are often considering precast concrete to provide a low-maintenance, durable, high-performance solution. There are three broad categories of architectural precast concrete wall system: *Conventional panels* use precast concrete as large format panels on the exterior acting as the exterior finish and providing the enclosure support function. *Double wythe insulated precast concrete wall panels* (sandwich panels) incorporate thermal insulation between an exterior finish

wythe and an interior support wythe. The exterior and interior wythes are connected with ties that maintain the structural integrity of the panel and provide the degree of composite or non-composite action desired. Finally, *veneer panels* comprise a precast concrete backup panel with small panel non-loadbearing cladding products (stone, metal, etc.) attached to the face. The discussion in this paper applies to precast concrete wall systems with effective “rainscreen” drained joints for rain water management (see example in Figure 1).

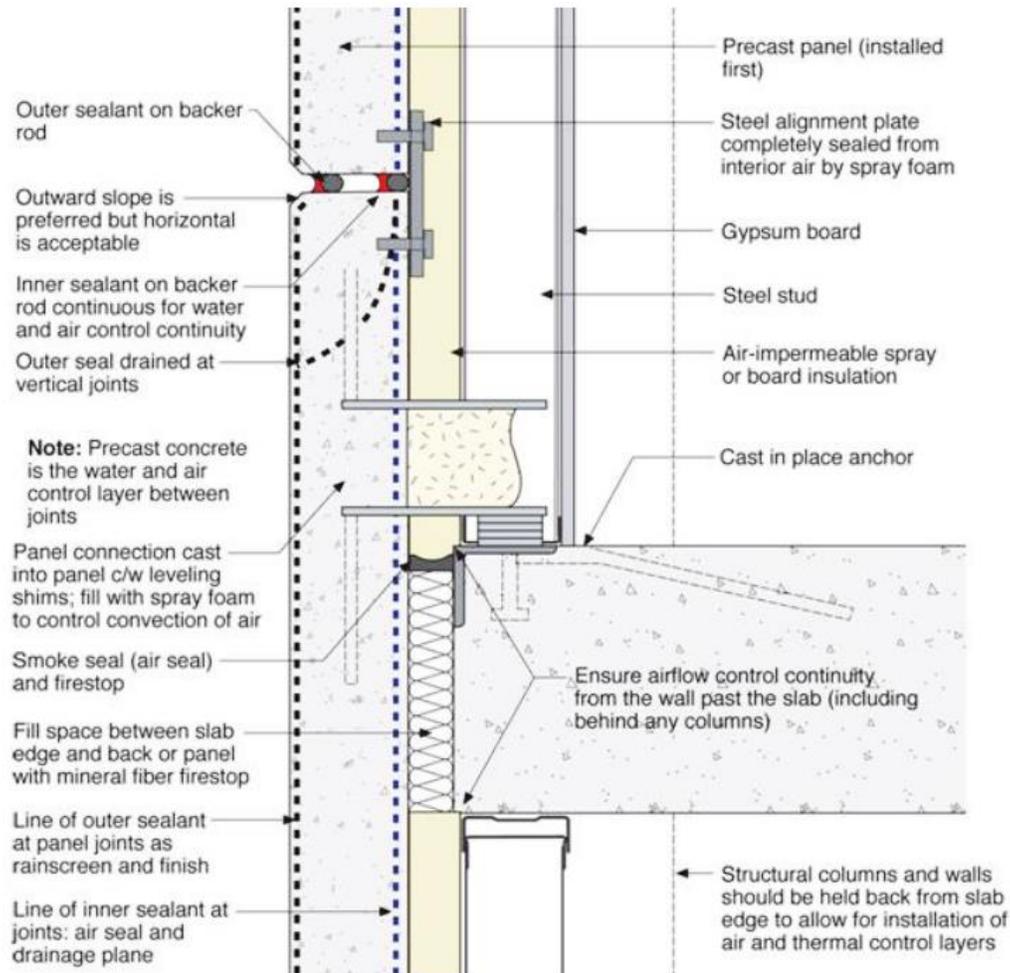


Figure 1: Conventional Precast Concrete Wall Assembly (Straube 2013)

Curtain walls are enclosure systems comprised of thin-walled metal framing, usually aluminum, with in-fills of glass, metal panels, or thin stone. The framing is attached to the primary building structure and provides enclosure support functions only and does not participate in primary building loads. The American Architectural Manufacturers Association (1996) defines window wall as *a type of metal curtain wall installed between floors or between floor and roof and typically composed of vertical and horizontal framing members, containing operable sash or ventilators, fixed lights or opaque (spandrel) panels or any combination thereof*. Such systems are popular because they provide a low-cost solution for enclosures with high window-to-wall ratios (WWR). In our experience, design teams often fail to recognize that systems with high WWRs have marginal performance in numerous areas, such as thermal comfort and energy performance (Straube 2008), as well as having significantly lower durability and resilience compared to opaque wall systems such as precast concrete.

2. DURABILITY

CSA S478-95 (R 2007) Guideline on Durability (CSA 2007) defines durability *as the ability of a building or any of its components to perform its required functions in its service environment over a period of time without unforeseen cost for maintenance or repair*. The standard provides a process for defining design service lives, comparing to predicted component service lives, and then a quality assurance program to avoid component failures. The standard also provides useful categories of failure as shown in Table 1 with examples specific to exterior wall systems.

Table 1 CSA S478-95 Categories of Failure with Wall System Examples

Category	Effects of failure	Wall System Example
1	No exceptional problems	Recoating, resealing, etc.
2	Security compromised	Wall movement causes door to not close properly
3	Interruption of building use - Repair requires discontinuation of services or dislocation of occupants	Excessive wetting of interior drywall
4	Costly because repeated	Window hardware replacement
5	Costly repair - Requires extensive materials or component replacement or extensive use of scaffolding	Window IGU replacement, brick ties rusted out, etc.
6	Danger to health or the ecological system	Excessive mould growth on or within walls
7	Risk of injury	Spalling masonry bits falling from building
8	Danger to life	Large chunks of cladding or glazing falling from building

Durability is also commonly attributed to materials and systems that can achieve a long service life with low anticipated maintenance requirements. First ongoing maintenance and then service life will be explored for both systems in terms of anticipated and unanticipated failure.

2.1 Ongoing Maintenance

Precast concrete wall panels should be installed with rainscreen water control using drained joints as shown in Figure 1. Quality silicone sealants used at the outer rainscreen seal in precast concrete systems last reliably for 25 years and often 35 years. Lower-grade sealants may only last 10 years and are not recommended. In both cases, the inner seal will probably need to be replaced with every second outer seal replacement (i.e., inner seals, protected from UV and direct water, tend to last twice as long). Hence, for a precast concrete wall system using a good silicone sealant one could assume replacement of the outer seal at 30 years and both outer and the inner seal at 60 years. Replacement is made relatively easy as the joints are exposed and accessible from the exterior, and are relatively wide. Precast concrete wall systems overhang floor slabs and separation walls avoiding additional seals at floor lines. Although potential complications can arise at the interface of the precast concrete wall system and the window or other wall cladding, design guidance for achieving maintainable rainscreen joints at such locations has recently been published by Straube (2013), which minimize these.

Curtain wall and window wall systems are installed with gaskets and sealant for air and water protection. The gaskets are often intended to last the service life of the wall system and will be discussed in the next section. Sealants are used onsite where window walls intersect exposed floor slabs and other cladding systems. In window wall systems, these joints are often not drained and rely on the outer exposed sealants for rainwater protection. The sealing is a likely point of failure since it is difficult to maintain and to avoid rain water entry. Furthermore joints are often difficult to access, increasing the cost of remediation where leaks occur. Sealant is often extensively used internally to provide the hidden water seal at aluminum framing intersections. Curtain walls designed as drained systems rely extensively on such hidden sealant. This sealant, while protected from sun and direct rainwater, can only be replaced

by disassembling the system, and is often highly stressed because of the small joint size, lack of backer rods, and large thermal movements of aluminum.

The various maintenance items are listed in Table 2, along with their estimated costs. The Net Present Value (NPV) has been calculated with a 10% discount rate for 60 year period. The Net Present Value of the precast concrete wall maintenance requirements are less than \$2 per sqm while those for the window wall are greater than \$10. This represents significantly less maintenance cost for precast concrete panel wall systems.

Table 2: Ongoing Maintenance Requirements

System	Maintenance Item	Frequency* (yrs)	Delay Start (yrs)	Cost** (\$/sqm)	NPV*** (\$/sqm)
Precast concrete wall	Outer seal replacement	30	-	\$20	\$1.21
	Inner seal replacement	60	-	\$25	\$0.08
	Fibreglass window gasket replacement (5% failure rate)	2	20	\$30	\$0.27
Window wall	Outer sealing replacements and at failed gaskets (20% failure rate)	2	20	\$30	\$11.20

* Based on author experience

** Based on author experience (note in fact these cost vary considerably in North America)

*** 10% discount rate for 60 year period

2.2 Service Life

Precast concrete wall panels are reinforced for crack control, and made of high-quality, factory-made concrete with very low water-to-cement ratios. The panels are generally considered unrestrained and their connections are designed to not be affected by building movement. For these reasons they are reliable water barriers that last the life of most buildings. Some Insulated Glazing Units (IGUs) will fail throughout the life and the windows will likely need to be replaced at 40 years.

Kesik (2011) describes the common service life of window wall systems typically used in Toronto and summarized here. A common scenario involves isolated gasket failures after 3-7 years which are identified by rain water leakage and are remediated on an as-required basis. These failures spread until the repeated nature of the issue justifies resealing the entire exterior face of the window wall. This cost varies depending on the height of the building and the ease of vertical access. This remediation extends the life of the facade 10 to 15 years. Hence, some experts forecast that many of these systems will need extensive renovation or replacement after only 15 to 20 years post-construction.

Table 3: System Replacement Costs Over 60 Year Period

System	Maintenance Item	Frequency (yrs)	Delay Start (yrs)	Cost* (\$/sqm)	NPV** (\$/sqm)	CSA S478-95 (R 2007) Failure Category
Precast concrete wall	Replace windows***	40	-	\$750	\$4	1
	Replace Failed IGUs (2% failure rate)***	2	10	\$375	\$3	1
	Recoating precast	10	-	\$45	\$23	1
Window wall	Replace Failed IGUs (2% failure rate)	2	10	\$375	\$13	1
	Install cap bead over glazing tape	15	-	\$40	\$13	1
	System Replacement	40	-	\$800	\$18	3, 5, and possibly 6

* Based on author's experience

** 10% discount rate for 60 year period

*** Only 25% of the area is considered in this cost

Within our analysis we use much more optimistic assumptions. Within a 60-year period, window wall systems is replaced once with resealing every 15 years. IGUs are assumed to be replaced at the same frequency as for the fiberglass windows. This amounts to a significant difference in NPV as shown in Table 3. The Net Present Value (NPV) has been calculated with a 10% discount rate for 60 years as before. The cost for the window wall is double that of the precast concrete system and punched windows. Furthermore, window replacement in the precast concrete walls and various maintenance items can be completed with little interruption to the building use. Replacement of large areas of the façade will significantly interrupt space use and be costly due to the extent of work required. The failing of rain water seals in window walls can also potentially lead to interior moisture damage and mold growth. These additional costs are not included in the NPV costing.

The total Net Present Value of system replacement costs for the precast concrete wall system were calculated to be a total of \$30 while the window wall system was \$44. It is noted that the costs used this analysis and discount rate will vary considerably between buildings and locations. However, the differences in performance are quite drastic and such differences are not expected to change the general conclusions. This is reflected in the higher predicted life cycle costs reported in the recent Hanscomb study (Hanscomb 2016) for window wall versus precast walls for major cities across Canada. This difference in cost reflects the superior durability of precast walls relative to window wall systems.

3. RESILIENCY

The Centre for Resilience of Critical Infrastructure [anon, 2016] defines resilience as *that essential ability of an operation to respond to and absorb the effects of shocks and stresses and to recover as rapidly as possible normal capacity and efficiency*. Operations can simply be the livelihood of high rise condo dwellers. Other buildings contain complex operations like server farms or manufacturing facilities. Most operations require human assistance (occupancy) and require a level of space comfort and security.

Pilot credits targeting resilience have recently been introduced to Version 4 of the Leadership in Energy and Environmental Design (LEEDTMv4) rating system (USGBC 2016). The first two credits *assessment and planning for resilience* and *design for enhanced resilience*, mostly target natural disasters induced shocks and stresses. The third credit entitled *passive survivability and functionality during emergencies* has the intent of *ensuring that buildings will maintain reasonable functionality ... in the event of an extended power outage or loss of heating fuel*. This credit addresses both natural and human-made disasters.

3.1 Passive Survivability – Thermal Resilience

The LEED “Passive Survivability and Functionality During Emergencies” pilot credit has a *Thermal Resilience* option whose intent is *to ensure that a building will maintain livable conditions in the events that all relevant power and thermal utilities are lost*. It requires demonstration through thermal modeling that “livable temperatures” can be maintained during at least 7 days during peak summertime and wintertime conditions. Detailed guidance is provided where hours with indoor temperature 12°C during winter and above 30°C during summer in the absence of electrical power or natural gas need to be limited.

For example, the coldest winter week within Toronto’s CWEC2 (Canadian Weather for Energy Calculations) weather file (commonly used for energy modelling) is shown in Figure 2 along with the hottest summer week in Figure 3. During the cold period the temperature ranges between 0 and -20°C with an average of -10°C. These include days with little sunshine. Based on these observations, maintaining livable temperatures in wintertime will rely on adequate thermal mass and limiting heat loss. The summertime condition rarely exceeds 30°C but every day is relatively sunny. Hence, maintaining livable temperatures will rely on adequate thermal mass and limiting solar heat gain.

Hard floor surfaces, concrete slabs, and the use of double wythe insulated precast concrete wall panels with exposed interior walls can provide significant thermal mass to spaces. Options for limiting heat loss and solar gains will be explored in the next section.

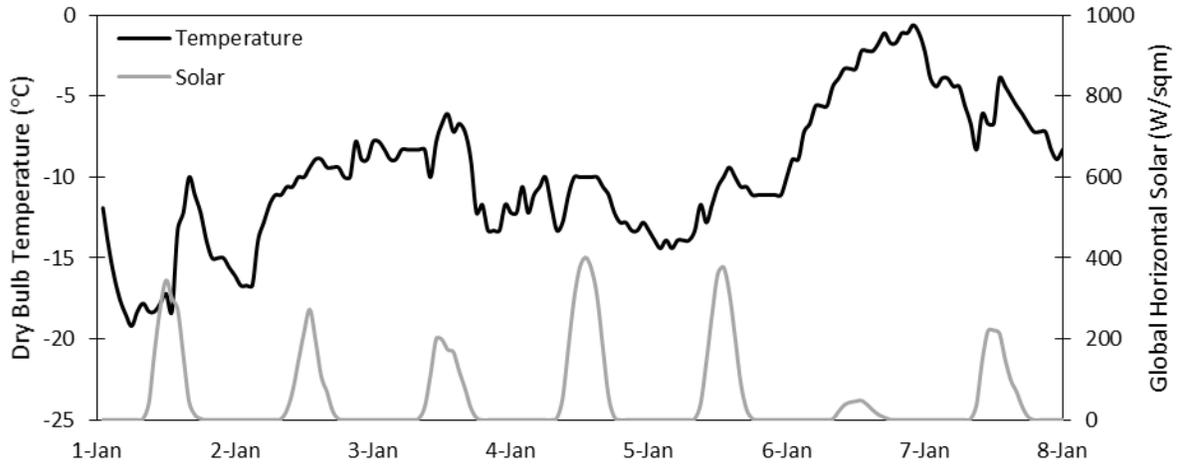


Figure 2: Coldest 7 Day Period in Toronto CWEC2 File

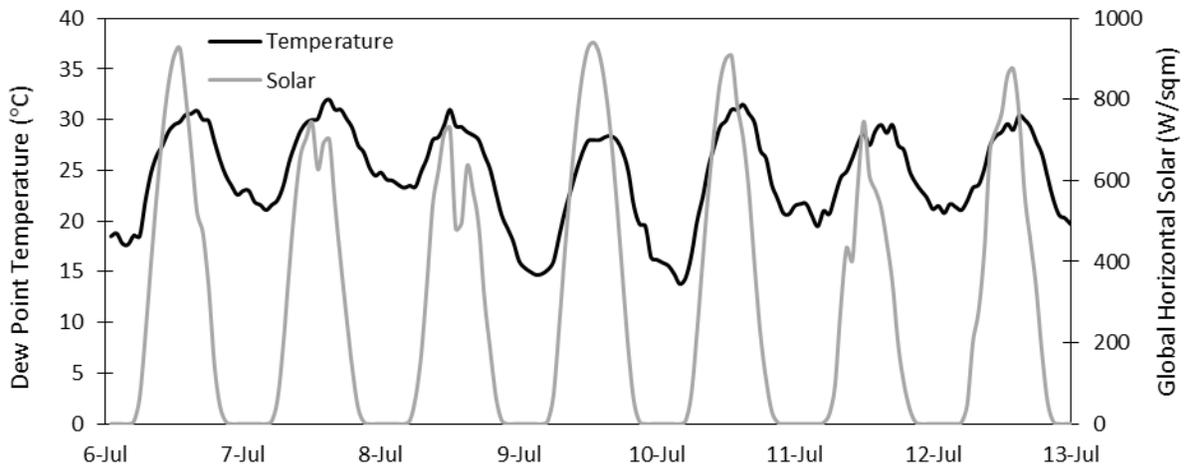


Figure 3: Hottest 7 Day Period in Toronto CWEC2 File

3.1.2 Whole Wall Performance

A range of different metrics are used to rate the thermal conductance of vision and non-vision wall assemblies. For non-vision walls it is typical to specify thermal resistance, R_{NV} , in an RSI ($^{\circ}\text{C m}^2/\text{W}$) or R-value ($^{\circ}\text{F ft}^2/\text{btuh}$) while U-value ($\text{W}/\text{m}^2\text{ }^{\circ}\text{C}$ or $\text{btuh}/\text{ft}^2\text{ }^{\circ}\text{F}$) is used for thermal conductance, U_V , of vision glazing. Building codes typically use a nominal R-value/RSI requirement which only accounts for the insulation while window U-values include surface films and can include the thermal bridging effects of framing and edge-of-glass construction. The thermal performance of an entire wall assembly can be drastically changed by modifying the Window to Wall Ratio (WWR) (Ross and Straube 2014). In order to compare the impact of WWR, glazing performance, and opaque wall performance, an equivalent overall whole wall thermal conductance, which combines the influence of all, is recommended as a single metric.

Thermal bridging effects not captured in the effective opaque wall performance can be captured by linear and point based thermal bridging factors ψ and χ , respectively. These have been published for a number of assemblies (RDH 2013, Higgins et. al. 2014, MH 2014) or can be derived from two and three dimensional thermal models. Whole wall equivalent conductance, U_{WW} , can then be calculated as

$$[1] \quad U_{WW} = [(1-WWR) \cdot A / R_{NV} + WWR \cdot A \cdot U_V + \Sigma(\psi \cdot L) + \Sigma(\chi)]/A$$

where A is the total area in m^2 and L are the lengths associated with linear thermal bridging factors in m.

Whole wall solar heat gain coefficient, $SHGC_{ww}$, capturing the effect of WWR and glazing performance, is likewise calculated from the vision SHGC as

$$[2] \quad SHGC_{ww} = WWR * SHGC.$$

To provide an example of how these metrics influence performance, consider an example with a baseline window wall system with a $1.99 \text{ W/m}^2 \text{ K}$ effective U-value and SHGC of 0.45. The non-vision areas are spandrel panel with R15 batt and an effective RSI of $1.33 \text{ K m}^2/\text{W}$ (MH 2014 section 1.1.1), linear thermal bridging heat loss at the slab of 0.63 W/m K (MH 2014 section 1.2.1), and at exposed intersecting concrete walls of 1.15 W/m K (MH 2014 section 1.5.1). It is assumed the space is bounded by intersecting walls and hence, half the heat loss from each wall is assigned to the space. The results for the baseline window wall systems are given in Figure 4 for a range of WWR values. Systems with almost all vision glazing are not uncommon and show high rate of heat loss and solar gain. Most of the heat loss is through the vision glazing for such designs. Any reduction of WWR will significantly reduce solar gains and reduce heat loss, as the thermal performance of the spandrel panel areas are better than the vision glazing.

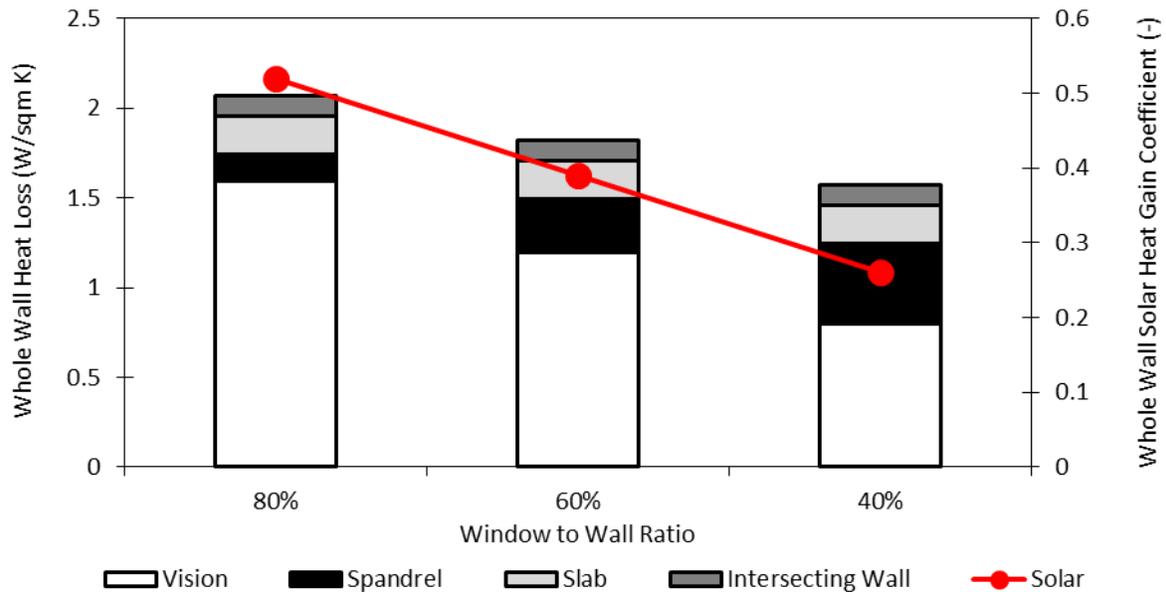


Figure 4: Whole Wall Heat Loss and Solar Heat Gain for Baseline Window Wall

Consider the influence of an upgraded window wall with improved glazing (either triple pane or interior low-e coating) resulting in a U-value of $1.34 \text{ W/m}^2 \text{ K}$ and SHGC of 0.35. R12 spray foam insulation (50mm) has been added to the interior of the backpan with an effective RSI of $1.81 \text{ K m}^2/\text{W}$ (MH 2014 section 1.1.2), linear thermal bridging heat loss at the slab of 0.63 W/m K (MH 2014 section 1.2.1), and at exposed intersecting insulated concrete walls of 0.82 W/m K (MH 2014 section 1.5.2). The results for the upgraded window wall case are shown in Figure 5. There is a 25% reduction in heat loss between the baseline and upgraded window wall system which will translate into occupant being sheltered in the building for much longer during a power outage during the winter.

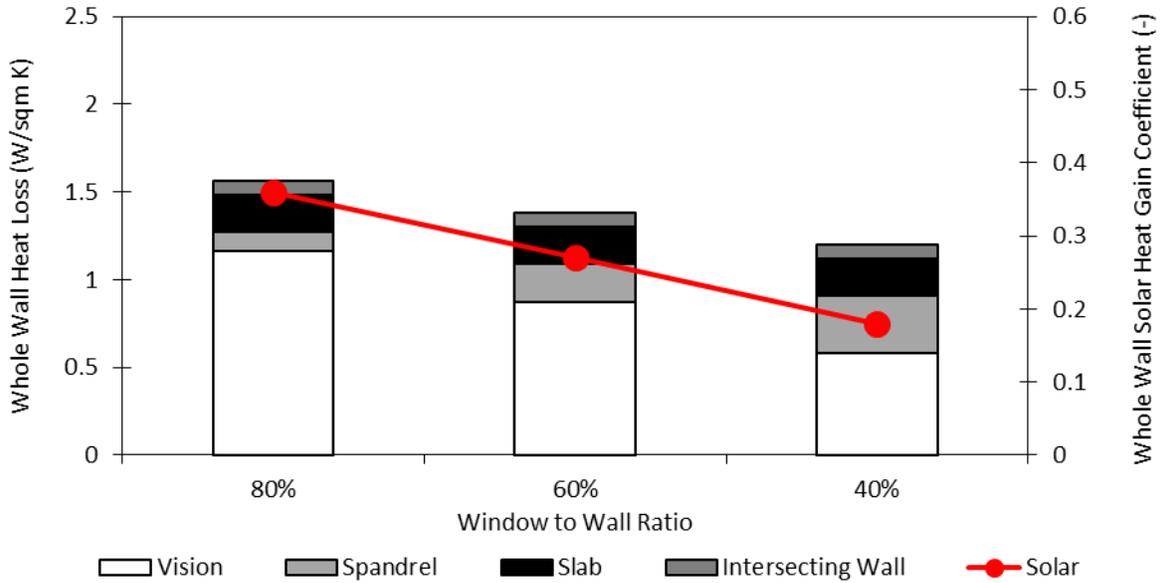


Figure 5: Whole Wall Heat Loss and Solar Heat Gain for Upgraded Window Wall

For the precast concrete enclosures 75 mm of 0.036 W/m² K continuous interior insulation is assumed with 25 mm of this mineral wool bypassing the slab. The thermal bridging effects of anchors, slab and intersecting walls (assumed to be similar to slab) are taken from Straube (2016). A double wythe insulated precast concrete wall panel would perform even better because of its internal thermal mass but these are not often used in high-rise residential buildings. Similar performance for the vision areas as the window wall system are assumed. The results are given in Figure 6. A 20% WWR case is added in lieu of the 80% WWR case as it is much more likely to be pursued with this wall system. Changing from a baseline 80% WWR window wall system to a low WWR baseline precast concrete wall system can cut winter time heat is half and summer solar gains in half or more.

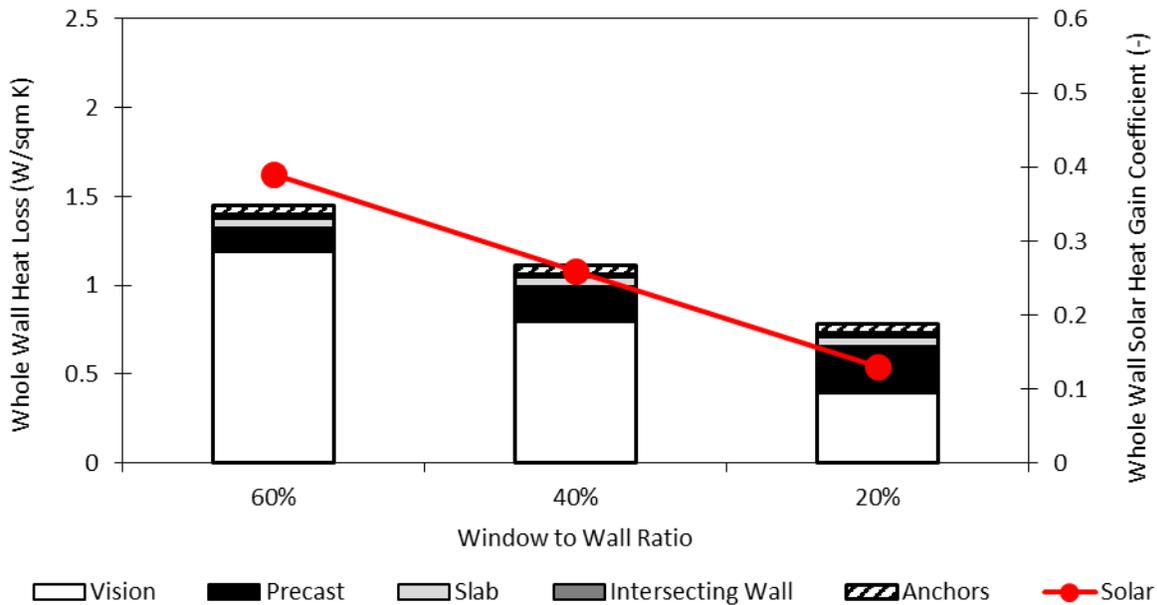


Figure 6: Whole Wall Heat Loss and Solar Heat Gain for Baseline and Upgraded Precast Concrete Wall System

The upgraded precast system is also a conventional precast concrete wall system with 150 mm of 0.024 W/m² K continuous interior insulation with 100 mm of fire-resistant stonewool insulation bypassing the slab. The thermal

bridging effects of anchors, slab and intersecting walls were also taken from Straube (2016). It is assumed that triple pane fiberglass framed windows are used with U-value of 1.16 W/m² K and SHGC of 0.36 (e.g., Thermotech 2016 awning window 302 HM TC88, #3, #4). Note that fire codes currently limit the use of fiberglass (combustible) framing for high WWR facades. The results for the baseline precast concrete wall are given in Figure 7. The upgraded precast concrete wall system has approximately half the heat loss of 60% and 40% WWR upgraded window wall systems. Using the upgraded precast concrete wall systems would quadruple the thermal resilience (i.e., the amount of liveable time in winter based on heat loss reduction). In reality the cooling period stretches over days where such system could effectively maintain night time comfort conditions allow some day time heat gain and extend the liveable time period even longer. The further reductions in solar gain due to lower SHGC windows would also extend comfort conditions within the summer.

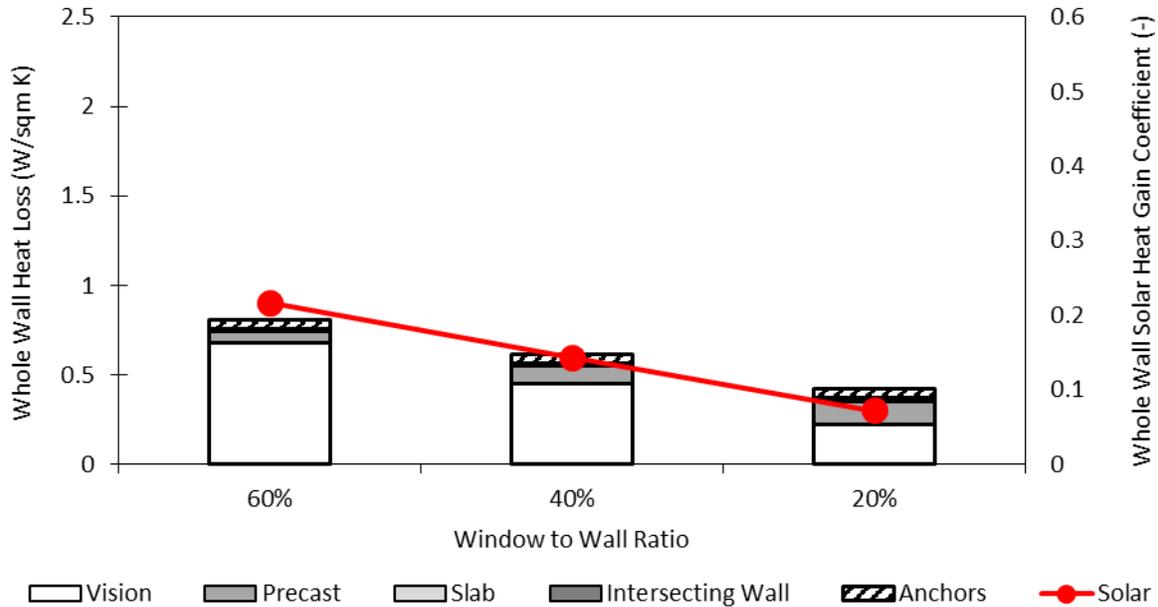


Figure 7: Whole Wall Heat Loss and Solar Heat Gain for Baseline and Upgraded Precast Concrete Wall System

There are many difference precast concrete and window wall systems available on the market. We do not expect the evolution of these product in North America to affect these performance differences significantly in the near future.

3.2 Security

Provision of security during disasters allows occupants to safely stay indoors, easing stresses on emergency services. LEEDv4 does not address this issue directly for wall performance. However, some obvious observations can be made. Precast concrete wall systems offer protection from projectiles (wind borne, thrown, shot, explosion related, etc.) limiting potential for injury to occupants who stay away from the windows. Highly glazed systems offer limited protection from projectiles. Falling glass from damaged areas presents significant injury risks to those below and would be significantly greater for window wall systems. The cost of broken windows, which in the case of window wall will include vision and non-vision areas, will present a significant cost burden. Most precast concrete wall systems will be little affected by most projectiles and will be functional without repair. This reduced repair burden will affect how quickly operations can proceed post disaster.

4. CONCLUSIONS

Two aspects of system durability have been investigated: ongoing maintenance and system replacement costs over the life of a building. The cumulative ongoing maintenance costs for precast concrete wall systems are much lower than those for the window wall system. The NPV of costs for the window wall replacement is an order of magnitude higher

than that for window replacement in precast concrete systems because non-vision areas do not need replacement and vision areas will last longer. Furthermore, replacement of isolated windows in the precast concrete walls can be completed with little interruption to the building use. These factors all demonstrate the durability features of precast wall systems.

Two aspects of disaster resilience have been investigated: passive survivability and provision of security. To assess passive survivability the LEEDv4 pilot credit criteria for maintaining livable conditions have been considered. For the Toronto, Ontario climate significantly limiting heat loss in winter and solar gains in summer along with provision of adequate thermal mass will be key to performance.

A comparison of selected wall systems is included in Figure 8. For winter time, going from a baseline 80% WWR typical window wall system to a 40% WWR baseline precast concrete wall system can cut heat loss in half. The upgraded 40% WWR precast concrete wall system has about half the heat loss of the 40% WWR upgraded window wall systems. Ideally using the upgraded precast concrete wall systems would quadruple the amount of livable time in winter based on heat loss reduction relative to common window wall systems with high glazing ratios.

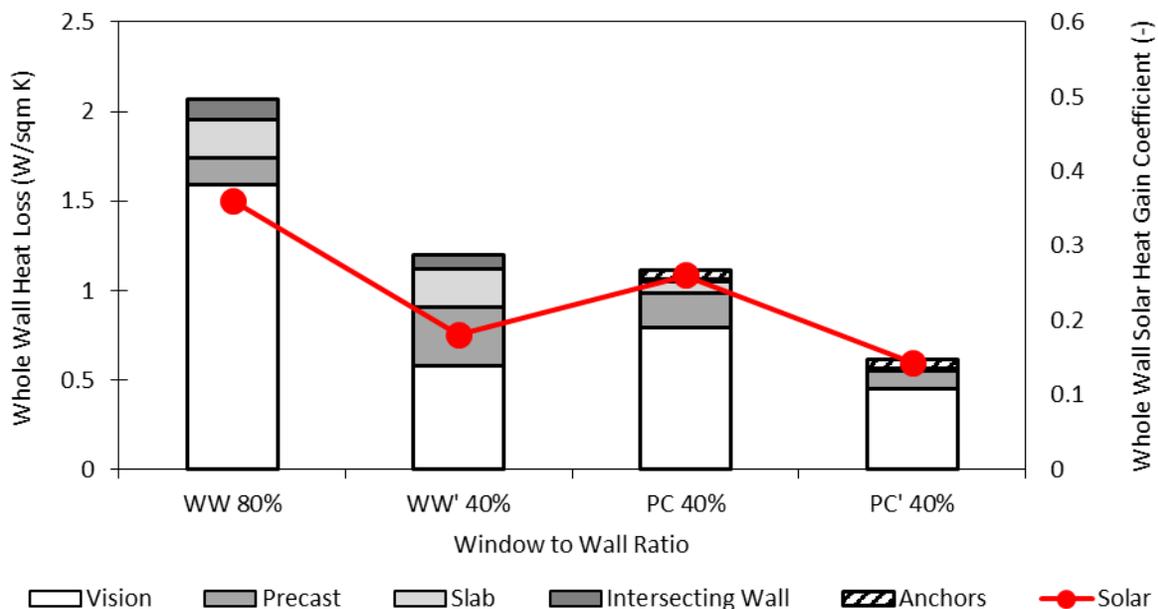


Figure 8: Whole Wall Heat Loss and Solar Heat Gain for Selected Walls

For summer time conditions the reduction of WWR and/or glazing SHGC directly reduce the solar gains for the space. Considering the common use of high WWR buildings being built in Toronto, Ontario and the limitation in reducing SHGC while providing high visible transmittance it would seem that reductions in WWR are the most likely path to improving thermal resilience.

Precast concrete wall systems provide increased security during disasters, as they offer protection from projectiles (wind borne, thrown, shot, explosion) limiting potential for injury to occupants who stay away from the windows. Most precast concrete wall systems will be little affected by most projectiles and will require little repair after the disaster.

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