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Thermal Breaks and Energy Performance in High-Rise Concrete Balconies


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Editor's Note:

Thermal bridging is a significant and under-explored issue in tall buildings, particularly where floor slabs are connected to balconies and façades. While the study described below is deliberately narrow in scope, we believe it raises issues of broad applicability for future designs. We note that even the most innovative façade technologies available today, such as the "raster façades" used on Tour Total, Berlin – a Finalist for the 2013 CTBUH Innovation Award – have yet to satisfactorily resolve the issue of bridging in a way that would make it broadly applicable and financially appealing to developers generally. North America lags behind Europe in this regard; I recently toured a LEED-Gold high-rise in Chicago that considered the issue, but found all the solutions on the market to be too expensive. We encourage further research and development in this vital field, so as to create more marketable and effective solutions. – ***Daniel Safarik, CTBUH***

Introduction

The building sector is the largest consumer of energy in the United States and Canada – approximately 30 to 40% of primary energy use. Space conditioning makes up nearly half of the energy use in residential buildings (DOE, IEA, NRCAN). This reality creates a significant need for increased energy efficiency in buildings. This need is widely recognized, and measures are being taken by North American jurisdictions, to implement increasing energy efficiency standards for buildings. Building envelope thermal performance is a critical consideration for meeting current energy efficiency targets, and will be an increasingly important factor, as authorities strive for low-energy buildings. To meet these challenges and completely realize the full potential of low-energy buildings, building envelope durability and occupant comfort must be considered concurrently with reducing heat loss when designing building envelopes. Otherwise, buildings will not operate as intended and resources will be wasted on components that need to be prematurely repaired or replaced. With this context in mind, this paper explores how thermal break technology for concrete buildings can help designers overcome the challenges of meeting energy efficiency standards.

Thermal bridges – highly conductive penetrations through the envelope – can have a significant impact on the thermal performance of the building envelope and whole-building energy consumption. Concrete balconies, formed by direct extension of the concrete structural floor slab, are an example of a significant thermal bridge that not only results in poor energy efficiency, but also results in cold interior surface temperatures during the heating season. The consequences of substandard interior surface temperatures include: increased risk of condensation and conditions favorable to mold growth. This paper examines the benefits of two methods for reducing thermal bridging for concrete balconies, compared to the prevailing method of continuous concrete projections.

Currently North American codes and energy standards that apply to high-rise residential buildings, with regard to energy efficiency requirements, have no specific prescriptive requirements for thermally broken slabs (for example ASHRAE 90.1, IECC, NECB, or MNECB). Moreover, the codes and standards do not explicitly address how thermal bridges at interfaces between assemblies, such as floor and balcony slabs, should be addressed in thermal transmittance calculations (U-values) that are necessary when determining

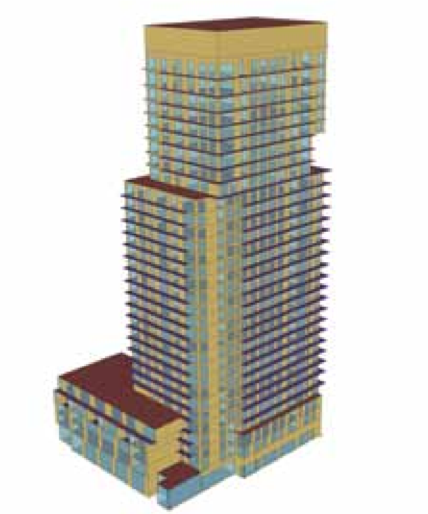


Figure 1. Study multi-unit residential high-rise building.

compliance. Some codes and standards allow designers to ignore the impact of structural slabs if the cross-sectional area of the projection meets specific criteria. The lack of clarity and consistency often leads designers to overlook the impact of concrete balconies on thermal transmittance.

However, for some cases, the standards are clear that concrete slab projections must be considered when determining compliance, for example when determining compliance by performance paths where the balcony areas are greater than 2 to 5% of the total envelope area. Furthermore, research such as ASHRAE 1365-RP makes it more difficult to ignore thermal bridging where it has been demonstrated to have a significant impact on the overall thermal transmittance of the building envelope. This paper expands on 1365-RP by providing thermal performance data for thermally broken concrete balconies and examples of how the 1365-RP methodology can be applied in practice for the design of high-rise buildings. Examples include the following:

- How to effectively model several balcony scenarios using whole-building energy models to consider both heat loss (U-value) and thermal mass
- How thermally broken slabs can help achieve code compliance for energy efficiency requirements
- How thermally broken slabs reduce the risk of condensation and increase occupant comfort

Challenged by a dynamic market fostered by these new standards, the industry still holds the desire to minimize costs, changes to construction methods, and constraints on architectural design. The market desires window-walls spanning floor-to-ceiling and concrete balconies wrapping around a large percentage of each floor. This desire is supported by the cost-effectiveness of the system, advantages related to installation and construction sequencing, marketability, and architectural appeal. The downside is that the thermal performance of window-wall systems is typically poor. To overcome a marginally performing thermal envelope, heat recovery ventilators (HRVs) are used to lower loads related to ventilation, and batt insulation is placed behind the spandrel areas to optimistically meet energy codes.

Some people might think that the practice of providing a marginal thermal envelope alongside efficient mechanical systems is backwards. Some might question putting batt insulation behind spandrel sections because of the ineffectiveness of the insulation and increased risk of condensation on the metal back-pan for any quantity of air leakage. These are valid points from a technical perspective, and there are definitely more holistic approaches available.

However, this case study highlights the reality of a market solution that satisfies the current state of codes and standards in North America. The objective of this paper is to highlight how thermally broken slabs can help improve the thermal performance of the building envelope and help meet the objectives of building codes and energy standards, despite the current lack of prescriptive requirements for thermally broken balconies in North America.

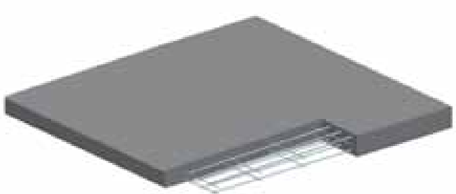
Building Characteristics and Construction Methods

These examples are covered by a case study of a multi-unit residential high-rise building. The case study building is representative of a common type of construction for high-rise buildings in some North American markets. The construction is very common for the market in question (Toronto), but the building envelope assemblies are not thermally efficient, and the codes in this jurisdiction have recently adopted more stringent energy standards.

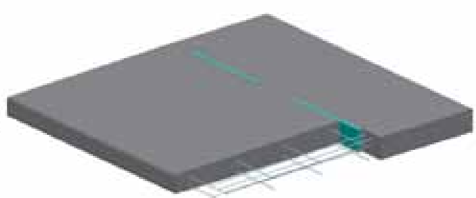
The study building is a multi-unit residential complex with 32 floors and 422 units (see Figure 1). It is designed with approximately 40% vision glass area and 3.5% exposed cantilever slab. The opaque area is largely insulated spandrel sections with metal back-pans.

The building envelope is primarily window wall, spanning floor-to-ceiling, and concrete balconies wrapping around large percentages of each floor. Three types of balcony connections were considered for this study (see Figure 2):

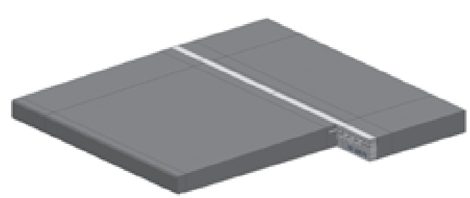
a. Cantilevered concrete balcony without interruption between the interior floor slab and exterior slab extension – **conventional construction**
b. Cantilevered concrete balcony with interruptions consisting of reinforced concrete (500 millimeters) and rigid



a. Conventional solution with continuous concrete slab.



b. Site solution with intermittent reinforced concrete and rigid insulation



c. Manufactured structural thermal break technology.

Figure 2. Balcony connection details.

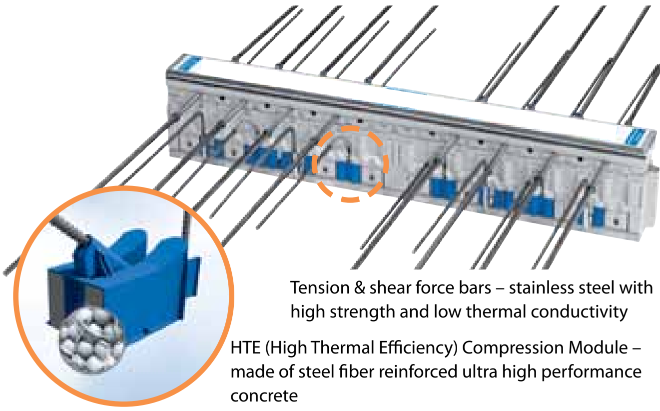


Figure 3. Detail of manufactured structural thermal break technology (MSTB).

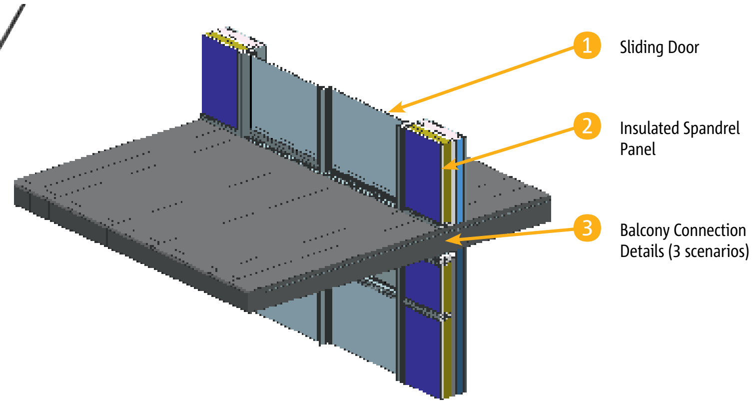


Figure 4. Wall assembly.

insulation (880 millimeters) of 400 millimeters thickness – **site solution**

c. Cantilevered concrete balcony with a **manufactured structural thermal break**

Manufactured Structural Thermal Breaks (MSTBs)

With the aim of decreasing thermal losses at the connection, MSTBs optimize the function and performance of each integral element at the junction. The reinforced concrete (k = 2.3 W/(mK)) at the connection is replaced with an insulating material such as expanded polystyrene (EPS, typically k = 0.031 W/(mK)) to give an effective thermal separation in the slab. This is non-structural and constitutes the main body and surface area of the thermal break.

To conserve the structural integrity between the exterior elements (e.g., balconies and canopies) and the interior structure (e.g., floor slab), reinforcement bars are used to connect both sides and transfer loads (tension and shear). These traverse the insulation body of the thermal break and are typically made of high strength stainless steel (k = 15 W/(mK)), instead of normal reinforcing steel (k = 50 W/(mK). This not only reduces thermal conductivity, but also guarantees longevity through its inherent corrosion resistance. To transfer the compression loads, the thermal break uses special high-strength concrete modules (k = 0.8 W/(mK)), as these again offer better thermal performance in comparison to normal steel and stainless steel.

Typically a range of thermal breaks is available from the manufacturer, depending on the load requirements and deflection criteria, so that the optimal solution between structural and thermal performance can be found (see Figure 3). The thermal break considered for this study provides enough structural integrity for a balcony with a cantilever length of 1.8 meters and a thickness of 200 millimeters.

Modeled Window-Wall Assembly

For the thermal analysis, each modelled scenario included a generic window-wall system that incorporated an opaque spandrel section and a sliding door (see Figure 4 and Table 1). The spandrel sections are insulated with a total of R-21 nominal insulation, split between an insulated metal back-pan and steel stud cavity behind the spandrel sections.

The window-wall system (vision and spandrel sections) spans floor-to-ceiling at the balconies and at typical vision areas. The U-value of this system is based on double-glazed, argon-filled, low-*e*, warm-edge spacers, with a thermally broken aluminum frame.

Mechanical and Electrical Systems

The mechanical system includes a four-pipe fan coil system with hot and chilled water supplied from a boiler plant (85% thermal efficiency) and water-cooled chiller plant (Coefficient of Performance (COP) of 6.1) for heating and cooling. Ventilation is provided by suite HRVs. Domestic hot water was not considered in the energy analysis. The average lighting power density for the whole

> “The thermal break considered for this study provides enough structural integrity for a balcony with a cantilever length of 1.8 meters and a thickness of 200 millimeters.”

Section	U_{si} (W/m²K)	R_{si} (m²K/W)	U (Btu/hr ft² °F)	R (hr ft² °F/Btu)
Spandrel wall	0.8	1.25	0.140	7.1
Sliding door	2.7	0.37	0.476	2.1

Table 1. Thermal transmittance and effective R-value of building envelope components flanking the balcony floor slabs.

Slab scenario	U_{si} (W/m²K)	R_{si} (m²K/W)	U (Btu/hr ft² °F)	R (hr ft² °F/Btu)
Continuous slab (conventional solution)	4.88	0.20	0.859	1.2
Slab with intermittent concrete door (site solution)	3.86	0.26	0.680	1.5
Slab with MSTB	1.21	0.83	0.213	4.7

Table 2. Thermal transmittance and effective R-value of the balcony floor slab area.

facility is 8.7 W/m². The average plug load density is 4.1 W/m².

Analysis of Concrete Balconies In Whole-building Energy Models

Whole-building energy simulation software utilizes steady-state U-values to account for thermal resistance of the envelope and often uses separate dynamic response factors or functions to account for thermal mass. A common approach to define building envelope assemblies in energy modeling software is to build up layers in the front end of the software, then run simulations to determine the U-value and dynamic response factors or functions. However, some energy simulation software does not directly account for thermal bridging, but rather references third-party information or relies on the user to input values derived elsewhere. For layers with thermal bridging, adjustments can be made (framing factor or adjusted conductivity) to ensure the software correctly defines the U-values or requires direct input of U-values into the model. Generally, less attention is paid to the dynamic response factors, but the thermal mass function can be treated in a similar manner to the U-value.

For this study, 3D sections of the window-wall system at the intersection of the three balcony connection scenarios were completed using 3D heat-transfer software from Siemens called NX. The analysis utilized steady-state conditions, published thermal properties of materials, and product-specific properties. The modeling procedures and software were extensively validated as part of ASHRAE research project 1365-RP. The thermal analysis highlighted a strong lateral heat flow path from the floor slab through the window-wall system for all the scenarios. This lateral path is a result of a connected network of highly conductive materials that bypass the thermal insulation: the concrete floor slab, the steel studs, and the window-wall aluminum framing. The result is a higher heat loss through the window-wall spandrel section than if the spandrel section was considered without the floor and balcony slab. Therefore, the 3D heat flow results for the thermal transmittance are higher (worse) than compared to typical scenarios that assume parallel heat-flow paths for the floor/balcony slab and wall assembly.

For input into an energy model, a uniform U-value for the spandrel and sliding door sections for all the scenarios was determined from analysis of the 3D heat flow as presented in Table 1. The balance of the heat flow was applied to the slab section for each scenario established from the total heat flow through the total assembly (window-wall system and balcony slab) as summarized in Table 2. This approach allows the building envelope assemblies to be split up between vision and opaque elements and light and massive assemblies. Moreover, components with mass, such as balconies or floor slabs, can be separately modeled to account for both the thermal resistance and mass of the building envelope components.

Whole building energy analysis was completed using EnergyPlus software. For this study, conduction time series coefficients (CTS) were utilized to distribute the heat gain by conduction over a 24-hour period to account for the impact of thermal mass. This method is convenient because the CTS coefficients do not rely on construction details.

Results and Discussions

Thermal Analysis

The thermal analysis revealed that the MSTB decreased the overall wall thermal transmittance (the window wall has less resistance) and increased the overall thermal performance of the building envelope. This is contrary to most expectations, where the wall assemblies typically have better performance than do intersecting building components that involve structural members. Both the conventional and site solutions follow typical patterns, wherein the overall thermal transmittance increased across the balcony-floor slab connection.

Table 3, the results summary, shows that the manufactured structural thermal break effectively reduces the heat flow through or around the slab by 75% compared to a conventional continuous balcony. This is a strong contrast to the slab with intermittent concrete connections (site solution), which only provides a 21% improvement over a conventional balcony slab.

From a whole-façade perspective, across both opaque and fenestration elements, the average thermal transmittance is 1.55 W/m² °C (effective R-value of 3.7) for the conventional-slab scenario. By improving only 3.5% of the total vertical envelope area with the MSTB, the average thermal transmittance is decreased to 1.42 W/m² °C (effective R-value of 4.0), which is an improvement of 8%.

A primary difference between the MSTB scenario and the other two scenarios is that the floor slab will be much warmer in the winter. This is a benefit for condensation resistance and thermal comfort.

Table 3 also summarizes the evaluation of the condensation resistance of the floor slab against design conditions for Toronto's climate. An exterior temperature of –18 °C represents the 2.5% January mean temperature found in Canadian codes and is

Slab scenario	U-value of balcony slab area W/m²K (Btu/hr ft² °F)	Reduction of heat loss	Coldest concrete temperature[1] (°C)	Meets design criteria with regard to condensation resistance[2]	Meets code[3] (SB-10)	Heat energy savings
Continuous slab (conventional solution)	4.88 (0.859)	–	–0.5°C (31.1°F)	No	No	–
Slab with intermittent concrete door (site solution)	3.86 (0.680)	21%	1.5°C (34.7°F)	No	No	2.0%
Slab with MSTB	1.21 (0.213)	75%	7.0°C (44.6°F)	Yes	Yes	7.3%

[1] At design temperatures of -18°C (-0.4°F) Exterior and 21°C (69.8°F) Interior (close to 2009 ASHRAE Handbook – Fundamentals)
[2] Temperature greater than the dewpoint of interior air 5°C (41°F) at RH 35% and 21°C (69.8°F)
[3] Energy Efficiency Supplement (SB-10) of the Ontario Building Code requires to exceed by not less than 5% the energy efficiency levels attained by conforming to the ASHRAE 90.1-2010

Table 3. Results and analysis summary.

close to the 99.6% peak heating design condition of −18.8 °C, which is specified in the 2009 ASHRAE Handbook for Toronto. A typical design criterion for indoor humidity during cold weather design conditions, like Toronto, is 35% relative humidity (RH) at 21 °C. The dew point temperature for these conditions is 5 °C. As seen in Figure 5, the MSTB is the only option that provides interior slab surface temperatures above the dew point and therefore meets these design criteria with regard to condensation resistance.

Whole Building Energy Analysis

Table 3 summarizes the results of the whole building energy for each of the three scenarios. The results indicate that heating energy for the building is reduced over the conventional solution by 2.0% and 7.3% when going to the site-installed intermittent concrete and MSTB solutions, respectively.

A large factor limiting the potential for greater savings is the fact that the flanking building envelope components are not thermally efficient in terms of insulation placement and thermal transmittance. The potential to achieve better savings through higher thermal-performance envelopes is discussed below.

Slab scenario	R-12 opaque assemblies (wall)	Triple glaze windows	R-12 walls & triple glazed windows	R-15 walls & high performance triple glazed windows
Continuous slab (conventional solution)	4.2	4.6	5.5	6.9
Slab with intermittent concrete door (site solution)	4.3	4.7	5.6	7.2
Slab with Isokorb (Schöck solution)	4.6	5.1	6.2	81

Table 4. Overall building thermal performance for various envelope improvements.

Code Compliance

For commercial and mid-to-high-rise residential construction, many local, provincial, or state codes reference ANSI/ASHRAE/IESNA Standard 90.1 in North America. Standard 90.1 allows three path options for showing compliance: prescriptive, trade-off, and performance. This case study is located in Toronto, Canada. Similar to many codes, the Ontario Building Code (OBC) modifies ANSI/ASHRAE/IESNA Standard 90.1 to account for local practices and initiatives.

The Ontario Building Code (OBC) contains a supplementary standard, SB-10, to deal with energy for larger buildings. The prescriptive path is modified from ASHRAE 90.1-2010 by including the values from ASHRAE 189.1 for envelope requirements. For the performance path, compliance can be achieved by modeling energy savings 5% better than ASHRAE 90.1-2010 Section 11, 25% better than MNECB 1997, or by meeting ASHRAE 90.1-2010 Section 11, modified by ASHRAE 189.1.

This case study building does not meet the prescriptive requirements for the OBC because the spandrel sections do not meet the building envelope requirements of U-0.055 or R-13 batt plus R-13 continuous insulation, which would return the minimum R-values as per Table SB5.5.5-5 for steel-framed walls. The performance path was deemed the viable method for demonstrating compliance when all the building envelope assemblies were compared to the prescriptive requirements. For this case study, the Standard 90.1 performance path was considered, which requires that the building design to energy efficiency levels by 5% or more than those attained by conforming to the ANSI/ASHRAE/IESNA 90.1-2010 Section 11.

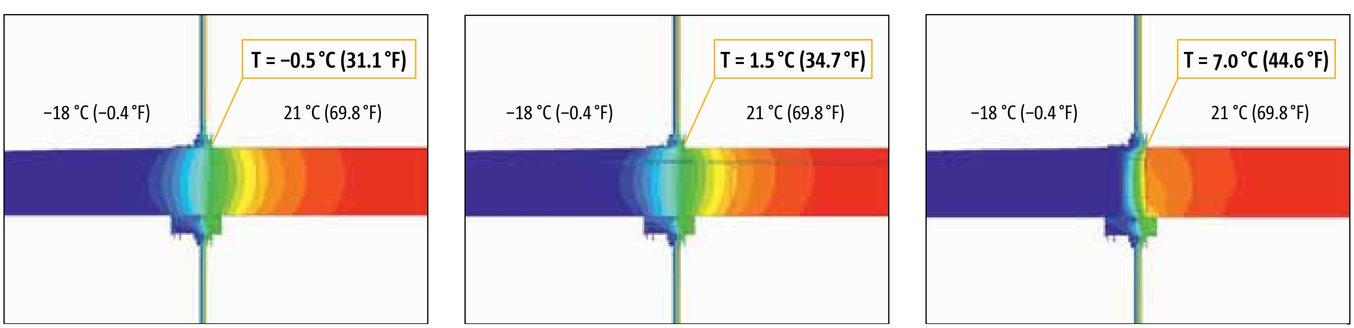
Compliance modeling per the Standard 90.1 performance path shows that only the MSTB scenario is compliant with the Ontario Building Code (OBC) for the study building, in contrast to the other two options that were below the "5% better than Standard 90.1" target.

Effects on Higher-Performing Envelopes

The higher the performance of the adjoining building envelope components, the more a conventional balcony slab will place a drag on the overall envelope thermal performance, consequently resulting in bigger gains for the MSTB solution. Table 4 summarizes the impact that the slab detail has on the overall R-value for several possible envelope improvements.

The slab U-values determined for this study were utilized for all the scenarios presented in Table 2. Therefore, Table 4 does not account for the impact of differences in thermal efficiencies due to thermal bridging at the intersection of components and misaligned thermal insulation. Additional improvements are expected for the manufactured structural thermal breaks when used in conjunction with efficiently insulated opaque assemblies, such as large areas of exterior insulated walls that place insulation in line with the thermal break.

The results in Table 4 are reflective for the study of a high-rise building, and will be more



Conventional solution (continuous concrete slab) — Site solution with intermittent concrete — MSTB providing significantly improved interior surface temperatures

Figure 5. Thermal profile of the three connection details.

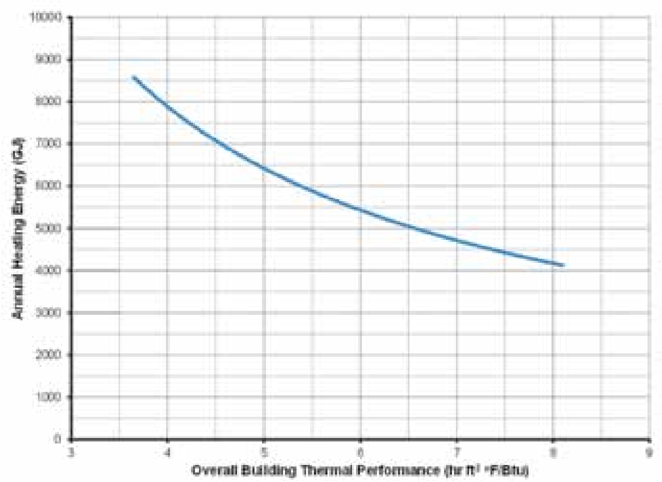


Figure 7. Energy use versus overall building thermal performance for the study building.

> "The 3D heat flow results for the thermal transmittance are higher (worse) than compared to typical scenarios that assume parallel heat-flow paths for the floor/balcony slab and wall assembly."

dramatic for projects with lower glazing ratios. The energy impact of the scenarios shown in Table 4 can be assessed by Figure 7, which shows the energy performance over a wide range of overall building thermal performance values. The graph illustrates that a small change in the overall building performance can have a significant impact on whole-building energy use.

Therefore, the savings related to the MSTB can be more significant for buildings with more efficient building envelopes, ranging from 7.3% for the study building, to as high as 14% for the scenario with the highest-performance envelope.

Conclusion

Thermal analysis of three methods for providing concrete balconies confirms that MSTBs provide substantial improvements over conventional continuous balcony slabs. The floor slab at the perimeter is warmer, thus providing benefits for condensation resistance and thermal comfort, and the heat loss through the balcony area is greatly reduced. In contrast, the site solution with intermittent concrete provides comparatively small improvements in thermal performance over a conventional balcony slab.

MSTBs deliver an effective thermally broken slab that reduces the heat loss by 75% and results in interior concrete surface temperatures that significantly reduce the risk of condensation and mold growth. A warmer temperature at the perimeter of the building also has the added benefit of improved occupant thermal comfort. By comparison, the intermittent-concrete site solution reduces the heat loss by 21% and results in concrete surface temperatures that are lower than typical cold-climate assumptions for the dew point of interior air at winter design conditions.

Looking at the study building from a whole-building perspective, the thermal breaks reduce the overall heating energy consumption by 7.3% compared to a building with conventional balcony slabs. Also, the study shows that MSTBs are most effective when utilized in conjunction with high-performance building envelope assemblies. The balcony cross-section area in the study building is only about 3.5% of the total exterior façade, but has the potential to provide 14% space-heating energy savings when utilized in conjunction with high-performance building envelopes. This impact will be more dramatic for buildings with lower glazing ratios. The study highlighted the impact for a cold climate, which provides a benchmark for heating dominated climates, but clearly the percentage gains will vary depending on the absolute heating loads and climate. Considering all the possible variations in construction and climates, we expect that the study building represents the lower end of the scale of potential gains that can be realized by MSTBs for heating-dominated climates.

This case study highlights how thermally broken slabs can help improve the thermal performance of the building envelope and help meet the objectives of building codes and energy standards, despite the current lack of prescriptive requirements to mandate thermally broken balconies in North America. With a drive to create low-energy buildings, MSTBs for balcony slabs should become an increasingly attractive solution and gain more recognition as a necessity for high-rise residential buildings. ■

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