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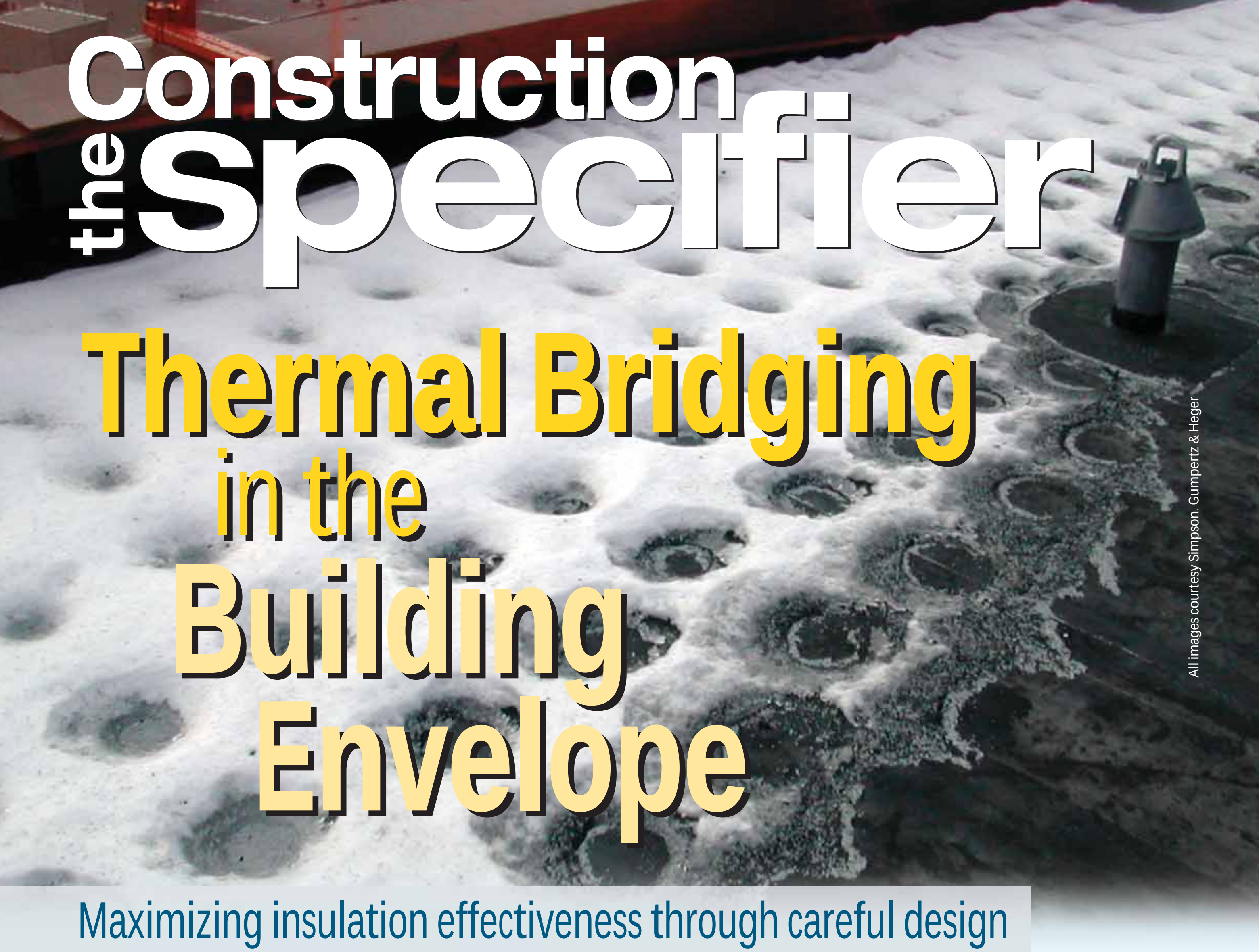

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Thermal Bridging in the Building Envelope

Maximizing insulation effectiveness through careful design

by Sean M. O'Brien, PE

The primary purpose of thermal insulation is to reduce conductive heat flow through the building envelope, thereby lowering heating and cooling costs while minimizing the potential of condensation on or within building components. Insulation should be viewed as an assembly rather than a material, since it is constructed in many different forms for various applications.

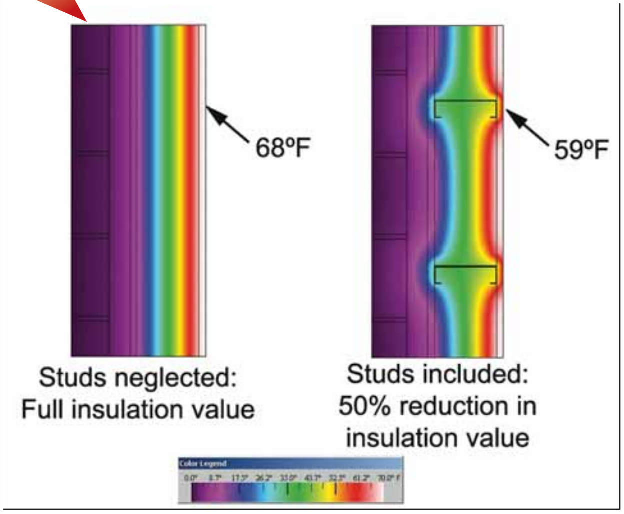
Due to the complexities of modern buildings, simply specifying insulation types (or even particular products) is not enough to ensure durable and reliable performance. In addition to the material's physical properties, other design elements of the insulation are also critical:

- its location within walls and roofs;
- its sequencing with respect to other layers in the assembly (especially air barriers and vapor retarders);
- its interface with surrounding or penetrating materials; and
- the continuity within and between insulating components.

As with other transport phenomena, heat naturally follows the path of least resistance. (See "Heat Transfer Basics," page 68.) When a highly conductive material like steel is placed in parallel with an insulating material, the majority of the heat transfer occurs through the metal, which offers less resistance to heat flow. The steel 'bridges' across the insulation, creating an easier path for heat to flow.

The oil embargo of 1974 was a major wakeup call to building owners and signaled the need for reduced heating and cooling costs to conserve energy. The natural choice of most owners was to increase the amount of insulation in the walls and roofs of their buildings, as well as to install insulating glass in windows, doors, and curtain walls. Thermal insulation soon became a primary concern of architects and builders, many of whom adopted a 'more-is-better' philosophy as opposed to a scientific approach to insulation design.

Figure 1



Computer simulation results showing effects of thermal bridging through steel framing.

New buildings are complex constructions that include a variety of materials with a wide range of thermal conductivities. However, building codes have only recently begun to address the problem of thermal bridging, which can significantly reduce the effectiveness of insulation and insulating components. Thermal bridging is now a generally recognized problem, but is not always properly addressed in designs. This can lead to problems ranging from excessive heat loss (or gain) to condensation and staining on interior and exterior surfaces.

Walls

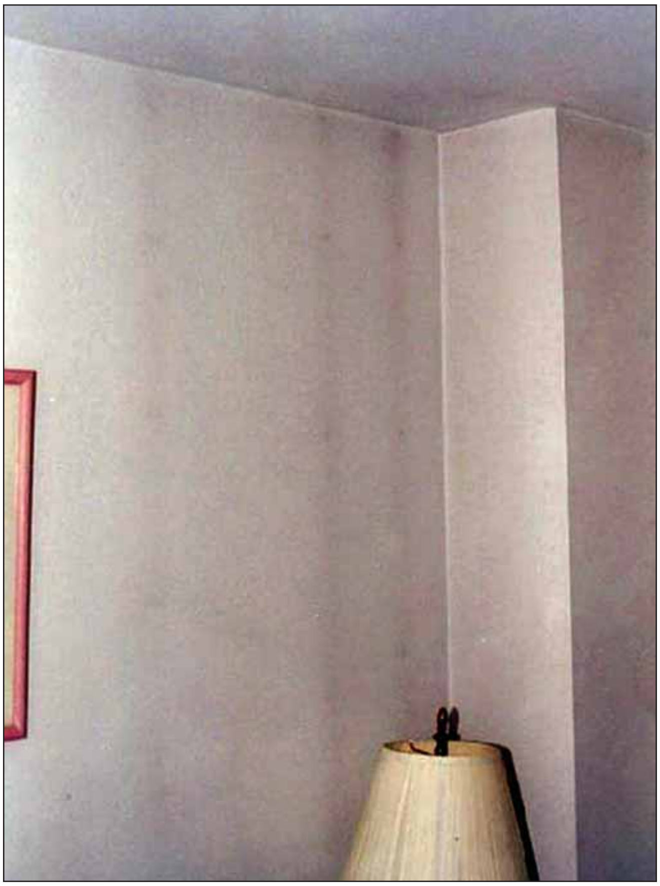
One of the most common thermal bridging problems occurs in framed exterior walls. Light-gauge steel framing is extremely popular due to its low weight, high strength, and ease of erection in the field. However, steel is also a highly conductive material, with a thermal conductivity more than 1000 times higher than typical building insulation.

In sheathed walls, glass fiber batt insulation is commonly placed between steel studs spaced approximately 410 mm (16 in.) on center (oc). These studs create ideal heat flow paths through the insulation. If one were to ignore the studs, the U-value of a typical brick veneer/stud wall assembly (assuming R-19 glass fiber batt insulation) is approximately 0.25 W/(m^2 x K) [0.044 btu/(h x sf x F)]. When one considers the same wall and includes the effects of 16-ga. steel studs installed 410 mm oc, the U-value is approximately 0.5 W/(m^2 x K) [0.088 btu/(h x sf x F)].

The addition of steel studs results in a 50-percent decrease in the overall thermal resistance of the wall. Figure 1 shows the results of a two-dimensional, steady-state heat transfer simulation of these walls using the Therm 5.2 computer program, with interior and exterior temperatures of 21.1 and –17.8 C (70 and 0 F), respectively.[1] Darker colors on the plots (which are shown in plan view) correspond to lower temperatures. If 50 x 150-mm (2 x 6-in.) wood studs are used in place of steel studs, the resulting reduction in thermal resistance is approximately 15 to 20 percent due to the relatively low thermal conductivity of the wood. However, wood studs are typically not a viable option for large commercial buildings.

The most obvious problem related to thermal bridging through steel studs is increased heat loss (or gain, depending on the season). If the effect of the studs is not taken into account by the mechanical engineer, heating and cooling systems can end up significantly undersized. A more subtle problem, often referred to as 'ghosting,' can occur when localized low temperatures at the studs lead to condensation and/or deposition of dust particles on the wall surface from the interior air.

Ghosting is more of a concern in buildings with high interior humidity levels or unusual concentrations of airborne contaminants, but it can occur in residential buildings under



In the above photo, localized cold spots at metal studs led to 'ghosting'—the deposition of contaminants from the interior air.

certain conditions (see photo at left). In hot, humid climates, a similar phenomenon sometimes happens on the exterior of walls. At high exterior temperatures, cold spots can form on the exterior of walls due to thermal bridging from the lower temperature of the interior air-conditioned space. Condensation, staining, and possibly microbial growth (*e.g.* mold or algae) can then collect at the cold spots.

Some building codes have recently included requirements for continuous insulation in wall assemblies, in addition to the insulation installed between studs. In Massachusetts, for example, prescriptive requirements for steel-framed walls include R-3 continuous insulation in addition to insulation between the studs. Continuous insulation (installed outboard of the studs) not only provides its own insulating value, but also helps minimize thermal bridging across the studs. This increases the effectiveness of the insulation between the studs. For the previously described steel-framed wall, adding R-3 continuous insulation outboard of the studs effectively increases the value of the wall by approximately R-4.5.

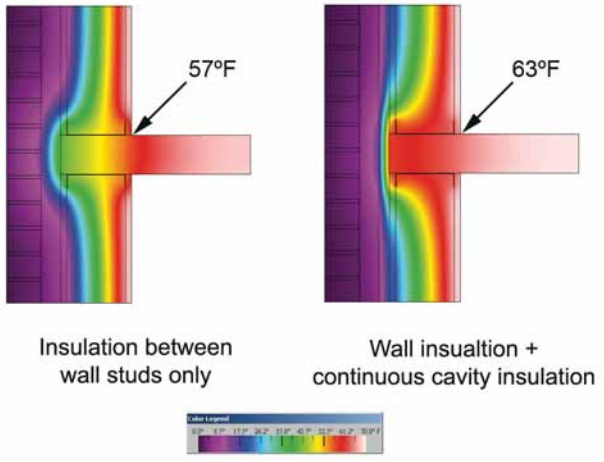
Continuous insulation can also reduce heat loss through typical conditions such as slab edges. In most stud-framed buildings, the studs on each level rest on floor slabs that penetrate the building insulation. Figure 2 shows simulation results for a typical slab-edge condition, both with and without R-3 continuous insulation in the cavity. Adding this insulation reduces heat loss through the slab edge by approximately 40 percent.

As the previous examples illustrate, continuity of thermal insulation is critical. To minimize thermal bridges and maximize the insulation's effectiveness, it should be installed outboard of the building frame to the greatest extent possible. Where thermal bridges do occur, care should be taken during design to minimize their effects. While it is possible to calculate heat loss due to thermal bridges in two-dimensional details (*e.g.* using the 'zone method' from the American Society of Heating, Refrigerating, and Air-conditioning Engineers [ASHRAE]), computer simulation is typically necessary for analyzing and optimizing complex constructions.[2]

Fenestration

Windows, curtain walls, and other components (referred to herein as 'fenestration products' for simplicity) typically have much less thermal resistance than opaque wall and roof sections. Average fenestration products have an effective thermal resistance of approximately R-2. Even the best assemblies barely break the R-4 mark, while adjacent walls typically have R-10 and higher.

Figure 2



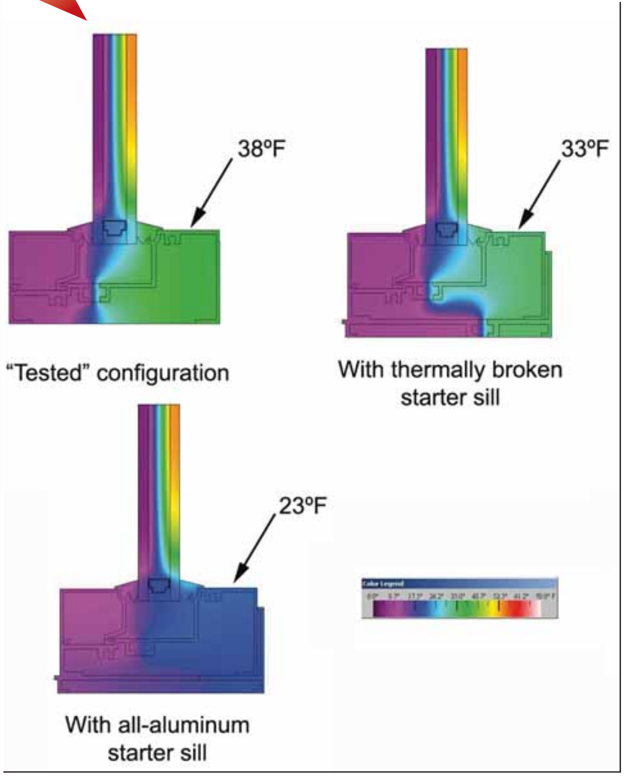
Computer simulation results showing effects of thermal bridging at slab edges.

Modern aluminum-framed assemblies employ features such as multi-pane insulating glass units (IGUs) and low-conductivity thermal breaks to reduce heat flow. However, due to the already low thermal resistance of these components, even properly functioning assemblies may experience condensation problems. Consequently, small thermal bridges through framing members and perimeter constructions can have a significant impact on heat loss and condensation resistance. To minimize the risk of these problems, the insulating components of windows must be made continuous with the insulation in the adjacent construction.

The most commonly used test standard for measuring the U-value and condensation resistance of fenestration products is American Architectural Manufacturers Association (AAMA) 1503-98, *Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors, and Glazed Wall Sections.* In this test standard, a specimen is mounted in an environmental test chamber within an insulated panel. The specimen is held in place by a combination of exterior clamps, tape, and friction.

While appropriate for determining the inherent thermal resistance of fenestration products, the test results do not provide an accurate picture of how the specimens perform in the field. In real buildings, fenestration products are connected to surrounding structures using metal clips, angles, or 'starter sills,' all of which provide additional heat flow paths at the perimeter. Due to this additional heat loss, the standard gives a measure of the best-case condensation resistance, but is not indicative of installed performance.[3]

Figure 3



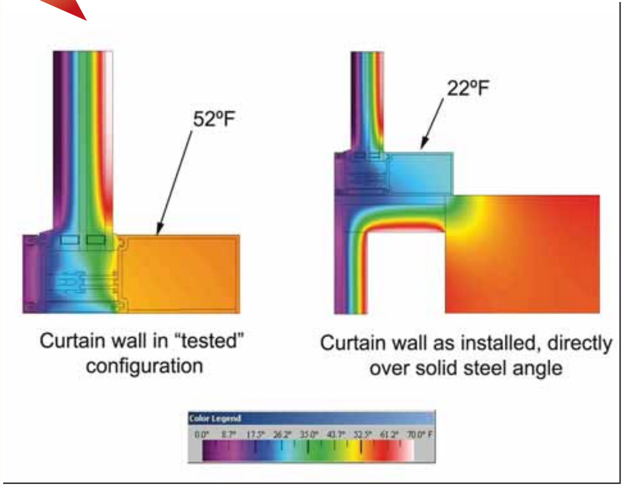
“Tested” configuration

With thermally broken starter sill

With all-aluminum starter sill

Computer simulation results showing the effects of ‘starter sills’ on window performance.

Figure 4



Curtain wall in “tested” configuration

Curtain wall as installed, directly over solid steel angle

Computer simulation results showing effects of thermal bridging below the curtain wall system on page 70.

When installing these products, care should be taken to avoid spanning across thermal breaks with attachment clips. While discrete perimeter clips may only cause localized heat loss (or lower interior surface temperatures), a larger problem occurs when starter sills and perimeter tracks are employed. These U-shaped channels are typically installed at window perimeters and may have snap-in legs on the front or back to facilitate loading of the windows. Tracks may or may not be thermally broken. However, regardless of the details of the track, these components are rarely included when a specimen is tested for thermal performance and condensation resistance. While testing products in every possible configuration is impractical for manufacturers, designers must still be aware of this fact when specifying products since starter sills are often the contractor’s or manufacturer’s preferred method of installation.

Figure 3 shows a series of Therm simulations of a thermally broken, exterior glazed window assembly within dual-pane insulating glass. The glazing in these models were simulated using the Window 5.2 computer program.[4] For these simulations, the perimeter of the window is defined as an adiabatic surface (*i.e.* one over which no heat transfer occurs) to approximate conditions during a laboratory test, where the window would be mounted in an insulated panel. Figure 3 shows the difference in temperature profiles and surface temperatures for three different conditions:

- window frame only;
- window frame with thermally broken starter sill; and
- window sill with all-aluminum starter sill.

In the worst case, the use of the all-aluminum starter sill reduces the thermal resistance of the window frame by more than 30 percent and lowers interior frame surface temperatures by as much as 8.3 C (15 F). Even the thermally broken track reduced thermal resistance by 10 percent and surface temperatures by 2.8 C (5 F) over the ‘tested’ assembly. Designers must be aware of these issues to avoid condensation problems and make accurate calculations for heating and cooling loads.

Since attachment details are not necessarily provided in the architectural drawings, these issues must be identified in the relevant shop drawings. However, placement of fenestration products within the building walls is typically a feature of the design, as are perimeter conditions within the opening.

One problem that can occur at perimeters involves the use of highly conductive materials in close proximity to the fenestration product within the opening. In brick veneer construction, steel lintels are often used at window heads to support the masonry above. In this case, the window should be placed inboard of the lintel to prevent heat from flowing through the steel and bypassing the thermal breaks. Having the window closer to the interior also increases its exposure to warm interior air—localized cold spots may develop in

Heat Transfer Basics

Heat is the energy by-product associated with the motion of atoms comprising a substance. Temperature is a measure of the average kinetic energy of a material, or a measure of the rate of how fast the atoms within that material are vibrating. The atoms in a hot (*i.e.* high temperature) material vibrate faster than those in a cold (*i.e.* low temperature) material. Heat transfer is simply the conveyance of energy from one material to another. It naturally flows from regions of high to low temperature by three transport methods—conduction, convection, and radiation.

Excepting a section on air leakage, the accompanying article focuses on heat transfer via conduction. Occurring through solids, liquids, and gasses, this is the transfer of heat through materials in contact with each other. For a single, monolithic material, the rate of conductive heat transfer depends on the temperature difference across the material and its thermal conductivity.

Thermal conductivity, expressed as W/(m x K), is a material property defining the rate of heat flow through that material for a unit temperature differential across a unit thickness. Similarly, thermal conductance describes the rate of heat flow through a defined thickness of material for a unit temperature differential.

A more commonly used measure of heat flow, or rather resistance to heat flow, is the R-value of a material—simply the inverse of thermal conductance. Since the purpose of insulation materials is to resist heat flow, the use of R-values (as opposed to thermal conductance values) makes more physical sense. Additionally, for one-dimensional heat flow, R-values can be directly added together to calculate the overall insulating value of an assembly.

Thermal conductance and R-values are useful for describing the one-dimensional heat transfer properties of materials (*e.g.* 50.8 mm [2 in.] of extruded polystyrene [XPS] has a value of R-10), but heat transfer in buildings rarely occurs in one dimension. This is true for component assemblies such as windows, which experience two- and three-dimensional heat flows through complex frame and glazing components. A more useful expression for defining heat flow is the overall transfer coefficient, or U-value.

The U-value, expressed as W/(m^2 x K) [btu/(h x sf x F)], is a measure of the total heat flow through a given material thickness (or a given component) in all dimensions. It represents the weighted average conductance for the various materials combined. In addition to conduction, the U-value takes into account convective and radiative heat transfer from surfaces and, for windows, convection and radiation through air spaces and glazing systems.

Due to the number of factors taken into account by the U-value, it is often necessary to determine this number experimentally or through computer simulation. U-values simplify heat flow calculations through building components, as it is only necessary to know the U-value of a component, its area, and the temperature difference across the component to determine the total heat flow (in W [btu/h]). As with thermal conductance, the inverse of the U-value is the overall thermal resistance, or effective R-value of a component or system.

deep interior window pockets due to lack of mixing with the conditioned room air.

Similar problems can occur at sills, as steel angles may be used for dead load support of fenestration. Figure 4 shows a Therm model of a triple-glazed, thermally broken curtain wall, both in the tested condition and as installed in a humidified archive in New England (where condensation resistance was a primary concern of the design). The curtain wall was installed directly against a 13-mm (0.5-in.) thick steel angle, which was a component of the existing curtain wall on the floor below.

This installation method led to a 45-percent reduction in thermal resistance and an average 16.7 C (30 F) reduction in interior frame temperatures. The photo on page 70 shows the interior surface of the frame during the winter, covered with frost because of the sub-freezing surface temperatures. The installation method for this high-end (and high-cost) assembly reduced its thermal performance to a level unsuitable for the intended use.

Roofs and parapets

Since framing members and other conductive components are typically installed inboard (on the 'warm' side) of the insulation, roofing assemblies with continuous insulation offer good protection against thermal bridging problems. Thermal bridging typically occurs at penetrations for rooftop equipment (*e.g.* air handlers and ductwork)—insulating these components is relatively simple, and most rooftop air handling equipment is pre-insulated to avoid heat losses and gains potentially affecting the operation of the equipment.

A subtler source of heat loss is the multitude of fasteners used to mechanically secure the roof insulation to the deck in some

Figure 5

*The above infrared image shows heat loss (*i.e.* yellow/red areas) through fasteners in a utility building clad with insulated metal panels.*

assemblies. The photo on page 62 illustrates an unmistakable sign of increased heat loss at roof fasteners. The depicted roof consists of a two-ply, modified bitumen (mod-bit) membrane installed over mechanically fastened insulation. The excess heat loss through the fasteners (as opposed to the field of the roof) raised surface temperatures enough to cause melting of the snow cover. Installing 5-mm [3/16-in.] diameter roof fasteners with 76-mm [3-in.] diameter steel pressure plates in an R-20 roof—at a spacing of one fastener per 0.1 m^2 (1 sf)—reduces the assembly's thermal resistance by approximately 15 percent (based on a three-dimensional thermal model created using the Heat 3D computer program).[5]

In the southeastern United States and along the Gulf Coast, where several fasteners must be used to withstand intense negative pressures from hurricanes, the thermal consequences can be the same—an increase in energy consumption due to 'loss' of cooling from the interior.

Although heat loss through the fasteners tends to reduce the temperature of the fastener tips penetrating the deck, the reduction in temperature is typically small enough so that condensation is only a risk in structures with high humidity. In these cases, staggered wood sleepers can be used to prevent fasteners from fully penetrating from the exterior to the interior. Alternatively, plate and fastener diameter can be varied to reduce thermal bridging. Since heat flow is proportional to area, reducing the size of plates and fasteners also reduces the area of conductive material in the insulation and lowers the rate of heat flow through the assembly.

The difference in cost between using staggered furring and installing typical mechanically fastened insulation is rarely justified by the energy savings associated with the reduction in heat loss. While adhered insulation eliminates the problem of thermal bridging, they may not be suitable for all roofing applications. In either case, designers must be aware of the limitations of each assembly.

A similar problem may also occur in some types of building walls. Figure 5 shows an infrared scan of a utility building clad with face-fastened insulated metal panels. During cold weather, the increased heat loss at the fasteners is clearly illustrated by the infrared image. As discussed above, this phenomenon causes cold spots and condensation on building exteriors in hot/humid climates, possibly leading to corrosion or microbial growth in those areas.

Thermal bridging is more likely to occur at parapets, especially those framed with light-gauge steel studs. Steel studs running vertically past the roof slab provide a clear path through which heat can bypass the otherwise continuous roof insulation. Even if the parapet cavity is filled with insulation, the parapet is surrounded by exterior air on three sides. Due to this exposure, the majority of the parapet will remain at or near the exterior temperature, acting as a 'cold sink' that draws heat from the interior.

Reducing the height of the parapets helps lower heat loss through these areas, but providing some type of thermal break between the parapet framing and the walls below is typically a more effective design strategy. If possible, parapets should be constructed above the roof with a thermal break between it and the roof slab, rather than as an extension of a wall below.

Heavy frost accumulation on this curtain wall sill illustrates the negative impact of perimeter thermal bridging on condensation resistance.

Additional Information

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B2010–Exterior Wall Vapor Retarders, Air Barriers, and Insulation
B2010–Parapets B2020–Exterior Standard Windows

Key Words

Division 07
Air leakage
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Abstract

Regulating heat flow is typically accomplished using insulation in roofs and walls, thermally broken fenestration products, and multi-pane insulating glass units (IGUs). However, these components are often used in conjunction with materials with significantly less resistance to heat flow. This article discusses the physical phenomenon of thermal bridging and examines common details and construction practices that can contribute to excessive heat loss in buildings.

Air leakage

While this article discusses problems associated with conductive heat flows, air leakage through building envelopes can lead to a different—albeit significant—form of thermal bridging. Just as solids such as brick and stone have the ability to store heat, so does air. Consequently, moving air can carry heat from one area to another. In a cold climate, air leakage from the interior to the exterior of a building can cause a significant increase in heat loss relative to that which normally occurs through conduction across walls and roofs. For example, the amount of heat lost through an unsealed electrical outlet (assuming a flow rate of 1 L/s [2.12 cfm]) is approximately the same as that lost through 2.8 m^2 [30 sf] of opaque wall (brick veneer over stud-framed wall with R-19 glass fiber batt insulation).

Similar to the steel studs' creation of a path of lower thermal resistance through insulation materials, air leakage paths offer a route for heat loss. While the heat loss occurs via convection rather than conduction, the result is the same (*i.e.* increased heat flow past thermally resistive materials). It is important to note the problems associated with airflow are by no means limited to heat loss, but those problems are beyond this article's scope.

Conclusions

All insulating building components must be designed and installed to work in unison and create a continuous barrier to heat flow in the building envelope. However, thermal bridging is not limited to conductive heat loss; air leakage through envelope components can contribute to increased heat flow and reduce the effectiveness of insulating components.

Coordination between architects, consultants, and contractors is necessary at all stages of a project to ensure assemblies are used to their full potential. The performance of a high-end, high-cost window can easily be degraded to that of a standard unit when thermal bridging at the window perimeter is not properly addressed. Due to the increasing complexity of buildings and building components, the plethora of building materials available, and the stringent requirements of energy codes, this integrated approach to insulation design is quickly replacing the 'more insulation is better insulation' mentality of the past.

Notes

[1] Therm 5.2 was developed by the Lawrence Berkeley National Laboratory (LBNL). Visit windows.lbl.gov/software.

[2] See Chapter 25 in the 2005 *ASHRAE Handbook of Fundamentals.*

[3] See this author's "Finding a Better Measure of Fenestration Performance: An Analysis of the AAMA Condensation Resistance Factor," which appeared in the May 2005 issue of *RCI Interface.*

[4] Window 5.2 was developed by LBNL. Visit windows.lbl.gov/software.

[5] Heat 3D was developed by the Blocon Corp. Visit www.buildingphysics.com.

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