Thermal Bridging: Observed Impacts and Proposed Improvement for Common Conditions

Andrea Love[1], Charles Klee[2]

ABSTRACT

This investigation seeks to quantify the effects of thermal bridging in commercial facades and then propose alternative solutions to improve performance. Utilizing infrared images taken from targeted assemblies at 15 recently completed buildings; we have calculated the actual performance of a range of façade types and conditions. We have compared these R-values with the theoretical, design intended R-values from drawings and specifications to quantify the discrepancy between design and actual performance. These differences were seen to range from greater than 70% less than the design intended R-value to those with negligible differences. This range shows the unintended impact that design details can have on thermal performance.

Based on thousands of images collected, we identified 16 common areas of thermal bridging that was commonly observed in the buildings surveyed. Broken into two broad categories of façade systems and transitions/penetrations, they range from such systems as curtain walls and existing wall renovations to conditions such as parapets and transitions to foundation. Using 2-D heat transfer simulations, models of these conditions were also developed. These models in conjunction with the infrared images were used to verify and understand the thermal bridges observed, as well as exploration of improved detailing. The study proposes alternatives to industry standards that can provide enhanced thermal performance.

The outcome of this research is a better understanding of thermal performance of commercial facades in order to help architects and building professionals understand the real impact of common thermal bridges and present alternatives to the industry standards that enhanced performance.

INTRODUCTION

Over the past twenty years, we have seen renewed interest in reducing the energy demand of buildings. At the building code level, groups such as ASHRAE have been steadily raising the bar on performance criteria for building envelopes and systems. The challenge faced by designers is to find and implement the technologies and solutions that can practically and economically affect the energy demands of our buildings. However, increasing the thickness of insulation materials will only go so far in impacting thermal performance, if we fail to consider how discontinuities such as thermal bridging affect the overall performance of the system.

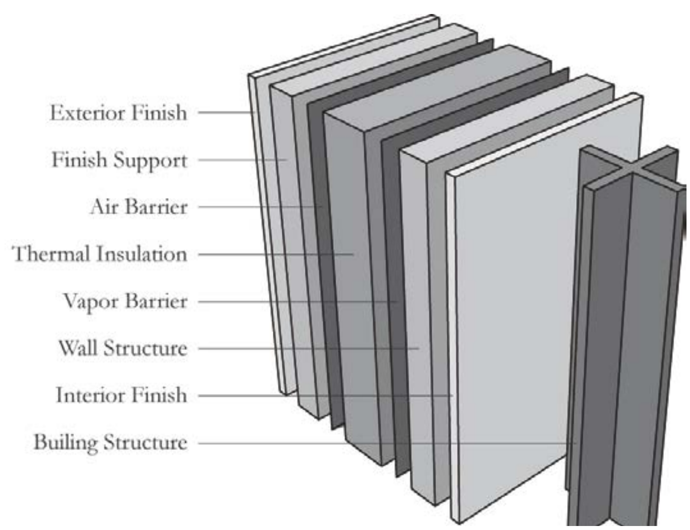


Figure 1: Diagram of Current Layered Facade Construction

---

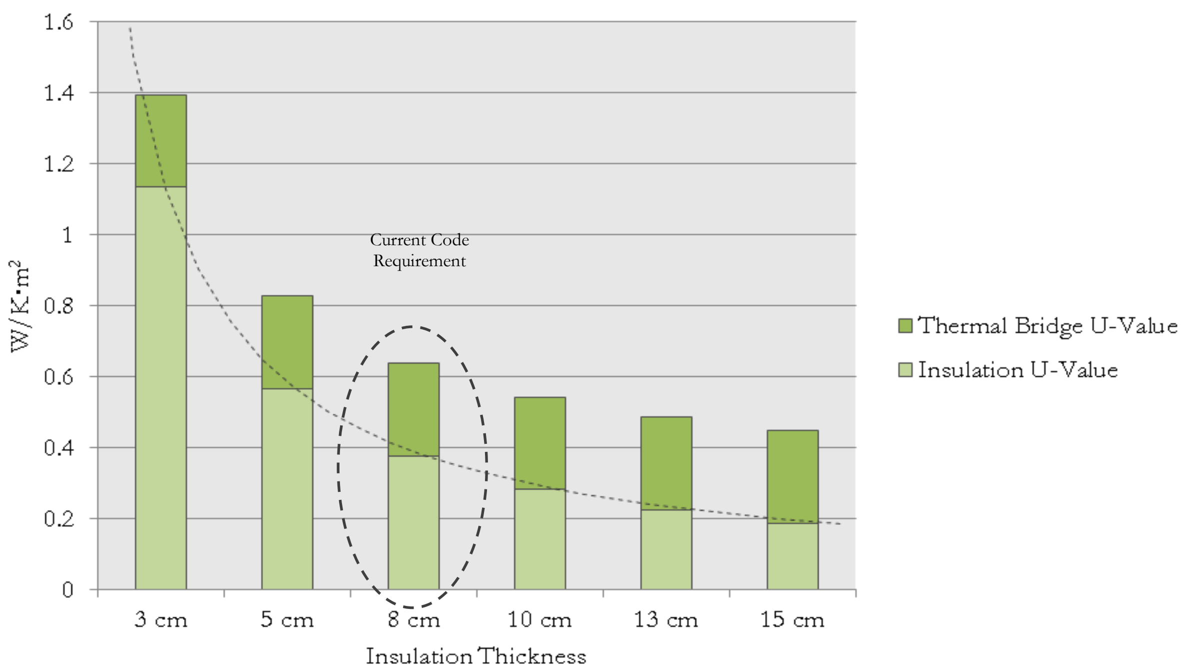
[1] Director of Building Science, Payette Associates, Boston, MA USA
[2] Principal, Payette Associates, Boston, MA USA

Thermal bridging in building construction occurs when thermally conductive materials penetrate through the insulation creating areas of significantly reduced resistance to heat transfer. These thermal bridges are most often caused by structural elements that are used to transfer loads from the building envelope back to the building superstructure. Though design professionals generally understand that thermal bridging is a concern, few can quantify the extent of its impact on building performance. With only a vague sense that this is a problem, it is unclear how aggressively we should work to minimize and mitigate the inevitable presence of thermal bridges. Research that has been published suggests that thermal bridges in conventional construction may reduce insulation effectiveness by as much as 40% (Morrision Hershfield 2011).

Considering this, we can see that the energy impact associated with thermal bridges will quickly become the dominant source of conductive losses as we increase insulation thickness in our pursuit of higher R values. This fails to acknowledge, however, that in many climate zones, energy code and standards already mandate "continuous insulation" values which are intended to take thermal bridges into effect. It is defined as follows:

> Continuous Insulation: *Insulation that is continuous across all structural members without thermal bridges other than fasteners and service openings. It is installed on the interior or exterior or is integral to any opaque surface of the building envelope.* (ASHRAE 2010)

Figure 2 : Chart of Heat Flow through Wall Assembly Showing Increase from Thermal Bridges



Accepting that this is an issue, the challenge becomes trying to evaluate how our facades perform and what can be done to improve them. Up until fairly recently, building construction was relatively simple and envelopes were essentially monolithic or limited to one or two layers of dissimilar materials. Because of this, the performance of traditional masonry and residential wood frame construction are better understood. Modern commercial construction, however, involves layered construction including rain screens, air barriers, vapor retarders, and a multitude of insulation technologies. The variables and interactions of these systems are complex and no longer suited to the simple arithmetic analysis that formed the basis of heat loss calculations 30 years ago.

The intent of this research is to bring rigor to the investigation of thermal bridges in commercial construction, both by quantifying and understanding how built façades are actually performing, and also to investigate proposed improvements to common problem details. By using thermal imaging equipment to quantify actual performance of built installations, we are able to calibrate theoretical models and suggest quantified performance improvements. Coupled with computer models of the assemblies in these images, we have investigated the impact of the thermal bridges and proposed improvements. Results show that it is possible to affect 50% or greater reductions in the impact of common thermal bridges by using careful detailing and products that are readily available on the market.

PROCESS OVERVIEW

The research project comprised of a multistep approach, starting with field observations of existing assemblies, followed by computer simulations of existing details and proposed thermal improvements.

Determining Design Intent R-values

Hand calculations of R-values based on the resistance of each layer of the envelope were based on shop drawings, construction documents, and/or Specification information, as appropriate. The surface resistance for air films, thermal resistances of plane air spaces, and material conductance when not known from manufacturer or project information, were taken from Chapter 26 of the 2009 *ASHRAE Handbook Fundamentals*. (ASHRAE 2009) Because these simplified one-dimension calculations do not take into account any thermal bridging, these values were used as the “baseline R-value” in our research as the best case scenario. It follows that assemblies whose observed and simulated R-values were similar had minimal thermal bridges. If there was a larger discrepancy between the hand-calculated, simulated R-value and observed R-value, thermal bridging was generally found to be playing a significant role in decreasing the thermal performance of the assembly.

In Field Observations

In order to understand how façades are performing in the field, we used a thermal imaging camera to locate areas of reduced performance and then determine the actual R-value of the area in question. Because we had access to a wide variety of common commercial envelope types and would similarly have access to the as-built detailing and materials submittals, we limited our investigation to projects that had been designed by our firm.

Two-person teams were deployed to 15 buildings and were asked to assess the general envelope thermal performance as well as scan the building envelope for areas that appeared to be performing differently. Because errors in calculating the R-value with the camera are minimized when the outdoor-to-indoor temperature difference is the largest, the teams went out to take measurements on cold days where the average outdoor daytime temperatures were less than 40˚F. Care was taken to avoid façades that were currently, or had recently been, in direct sun or were subject to internal heat sources or other factors that would skew results.

After collecting all of the field information, the thermal images were considered relative to the Contract Documents in order to identify the conditions that were most directly tied to thermal bridging issues as opposed to construction defects. This process served to eliminate problem areas such as missing insulation or air infiltration through discontinuities in air/vapor barriers though it may be fair to say that infiltration could also be a factor in decreasing the thermal performance.

Using the methodology tested by Madding (2008), we gathered the exterior air temperature, interior air temperature and the radiant temperature in order to calculate the as-built R-value of the assembly. The interior surface temperature of the façade was obtained from the infrared image, while simultaneously; a temperature data logger recorded the exterior air temperature. Using the time stamp on the thermal images, we were able to select the corresponding outdoor temperature with the infrared image.

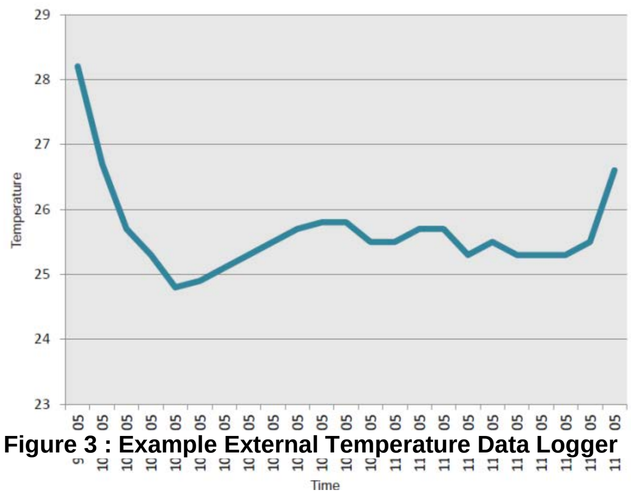


Figure 3 : Example External Temperature Data Logger

To obtain the interior air temperature we fanned a piece of card stock for a few minutes to bring it to air temperature then photographed it with the thermal imaging camera. Half of the card stock was covered in crumpled aluminum foil so that this would reflect the radiant temperature as well. This is possible because aluminum foil has a very low emissivity; it acts as a heat mirror and reflects the radiant temperature of the surface it is facing. With the emissivity of the interior material along with the exterior, interior, surface temperature and radiant temperatures we were able to calculate the R-value from the infrared images using the method documented by Madding (2008).

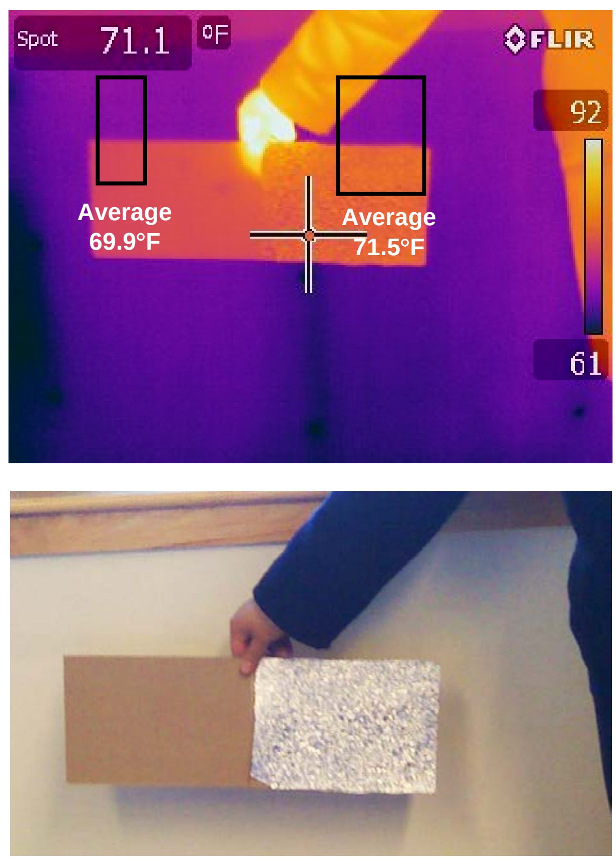


Figure 4 : Images of cardboard and aluminum foil tool used to determine and radiant temperatures

The more than 1,300 thermal images were collected and organized by assembly type and noted conditions that were likely to affect performance (i.e., the transition to a foundation wall or adjacency of a window). Having established a library of data, the research team was able to identify themes based on recurring problematic areas. We noted that they fell generally into two categories: one that is related to the structure that supports the façade and roof systems, and one that is more about material transitions and penetrations. Understanding these categories, we identified a handful of typical conditions that were selected for further investigation and analysis. Façade systems studied were:

- Rainscreens
- Masonry veneer façades
- Insulated metal panels

- Curtain walls
- Insulating of existing buildings

Conditions of transitions and penetrations that were selected for examination were:

- Window transitions to solid walls assemblies
- Foundation to above-grade wall transitions
- Transitions between façade systems
- Soffits
- Roof to wall transitions
- Parapets
- Roof penetrations
- Mechanical louver openings
- Beam embeds in existing buildings
- New slabs in existing buildings
- Seismic & movement joints

Simulated Performance

Because we would not be able to physically alter the built conditions, our methodology proposed to use computer simulations to test possible improvements to various construction details.

For its ease of use and ability to integrate into the design process, we selected the Lawrence Berkeley National Laboratory's THERM program, a 2D heat flow simulator, to determine R-values of complete assemblies including thermal bridges. For each detail, the first step in our process was to prepare models of the constructed designs, which were then calibrated to the actual performance measured in the field with the thermal imaging camera. Because neither the simulations nor the camera are a perfect technology, the process of calibrating the simulations with the thermal images allowed us to ensure that the models were accurate representations of what was observed in the field. With a validated THERM model in place, we were then comfortable trying design improvements and comparing the relative performance against the field measured performance.

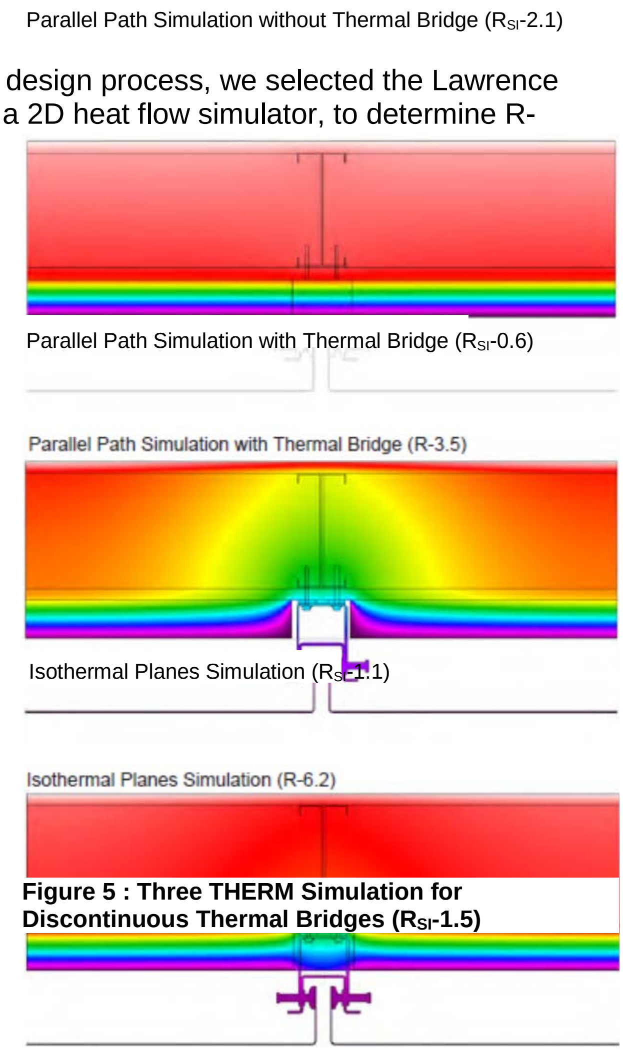


Figure 5 : Three THERM Simulation for Discontinuous Thermal Bridges (R_{SI}-1.5)

Because THERM is a two dimensional heat flow simulator, however, it is slightly limited in its ability to consider complex three-dimensional assemblies. It assumes that all modeled elements are continuous into and out of the screen. For discontinuous thermal bridges, such as bolts or clips, two methods were used to account for their three dimensional impact: the Parallel Path method and the Isothermal Planes method. Because the Parallel Path method tends to underestimate the impact of the thermal bridge and the Isothermal Planes method tends to overestimate its impact (Griffith, et al. 1998), the average of the two methods has been shown to be closest approximation. (Love 2011)

Once models of the existing conditions were established, we were able to better understand the thermal bridges inherent in the design, and develop alternative details that would improve thermal performance. Working from both the graphical and quantitative output from THERM, we strategically probed the models to identify the significant heat transfer elements within a given detail, and ultimately predict the performance improvements that might result from changes in detailing. This was particularly beneficial in the context of comparing different design options or the benefits of specialty products targeting thermal bridging performance.

THERMAL BRIDGING AREA OF INVESTIGATION: FAÇADE SYSTEMS
After evaluating our field data, we identified five basic façade types that would be generally applicable to modern commercial and institutional work and appeared to reflect slightly different challenges.

Rainscreens
Rainscreens have become increasingly popular for commercial façades in the past few decades due to their ability to control air and moisture movement. Because the cladding is held off the wall structure to form a drainage cavity while accommodating insulation and a robust air and vapor barrier, these systems require a secondary structural system of rails, Z-girts, and/or clips to support the cladding. Typically made of highly conductive metals, these structural members penetrate through the insulation causing significant thermal bridges. While insulation between steel studs has long been acknowledged in the industry to cause thermal bridging, these rainscreen supports have a similar impact thermally that until recently was widely overlooked. In our thermal images of rainscreen façades, we observed a decrease in thermal performance that ranged from 20% to 60% less than the design intended performance, with the majority around a 45-55% decrease. The systems we selected for study all had between two to three inches of insulation. We looked at a rainscreen with horizontal Z-girts, vertical Z-girts, and a clip-based system. Not surprisingly, the continuous Z-girts, whether horizontal or vertical, performed similarly. In both orientations, Z-girts demonstrated an R_{SI}-1.2 (R_{IP}-7.7) reduction in the assembly's R-value or roughly a 45-55% reduction in performance depending on the insulation thickness.

The façade with the clip system for the rainscreen performed much better than those with continuous Z-girts. Because of the intermittent nature of the clips, these systems performed well both in thermal images and in the computer modeling. The clip support system had half of

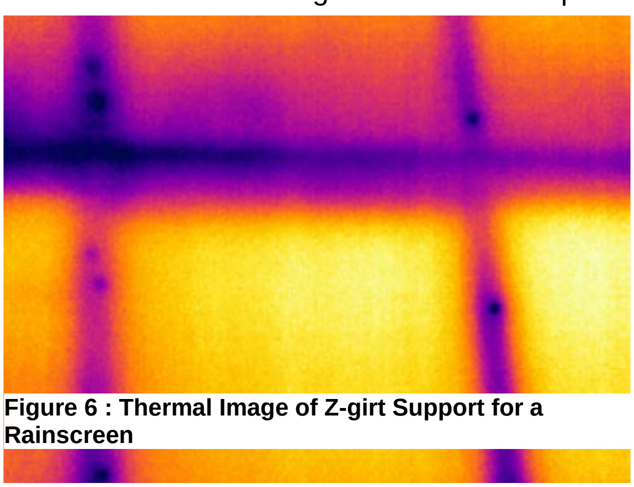


Figure 6 : Thermal Image of Z-girt Support for a Rainscreen

Figure 7 : Examples of Thermally Broken Rainscreen Supports

the heat flow of the Z-girts, or a 25% of the design intent. While the intermittent nature of the support system certainly improved the performance, we investigated ways to further improve the performance of rainscreen support systems.

A number of thermally broken Z-girt and rainscreen support systems currently exist on the market. As part of the research project, the team explored three of the thermally-broken options available. The first removed the support through the insulation with horizontal and vertical tube supports on the exterior and allowed only the stainless steel bolts to penetrate the insulation. The second system investigated a fiber glass clip system. This has the benefit of being intermittent, similar to the previous clip, but also uses a material that is more than 200 times less conductive than steel. The third system investigated was a discontinuous steel bracket with isolator pads on both the warm and cold side of the insulation, in order to minimize heat flow through the brackets. All three of the tested systems performed well. In general the R-value of the assemblies was only reduced by 10-15% due to thermal bridging through their support systems so that they achieved a minimum of R_{SI}-3.5 (R_{IP}-20) with four inches of insulation.

Masonry Veneer Walls

Masonry veneer wall systems are common for many building types in North America. Because they are rarely load bearing, they are dependent on shelf angles and a grid of tie-backs to structurally stabilize the assembly. Unfortunately, these supports and attachments form substantial thermal bridges and can dramatically decrease the overall thermal performance of the facades. In our observations with the thermal camera, we found masonry veneers generally performed at a 25-60% decrease in R-value when compared to theoretical calculations.

While masonry veneers can be supported without shelf angles by bearing on the foundation for limited heights, continuous shelf angles are typically required to support heights over two stories, and supporting every story is common in order to minimize deflection joints. These shelf angles typically run from close to the face of the masonry back through to the superstructure, passing through the insulation layer. Taken alone, these steel shelf angles account for an approximate 35% decrease in the R-value. That figure would be far worse if the steel was protected with highly conductive coated copper flashing as it may be been several years ago. Today, we might consider using a membrane flashing and making the entire angle out of stainless steel (which has 1/3 the conductivity of carbon steel). This sort of change could reduce the performance impact of the shelf angle from 35% down to 29%.

In order to truly minimize the thermal impact from the shelf angle, however, we investigated an option, advocated by Building Science Corporation (Lstiburek 2008), of supporting the shelf angle with evenly spaced blades or brackets that allow the shelf angle to remain entirely

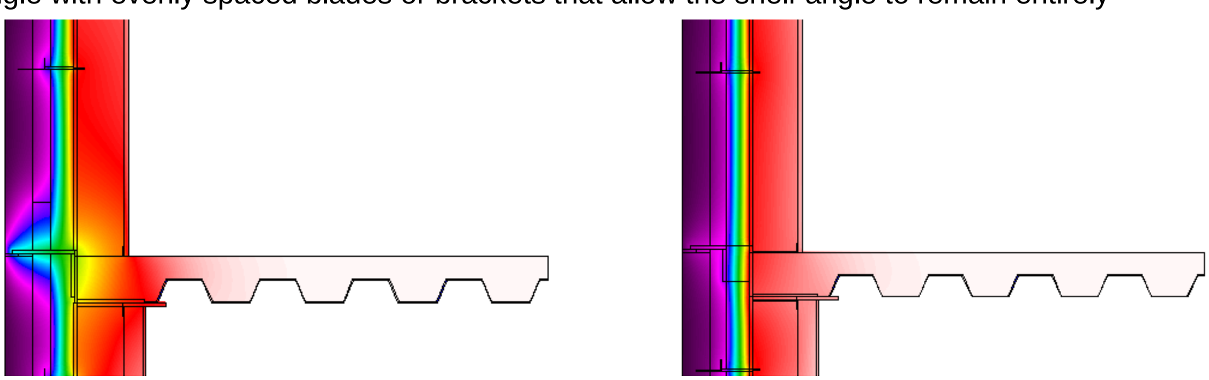
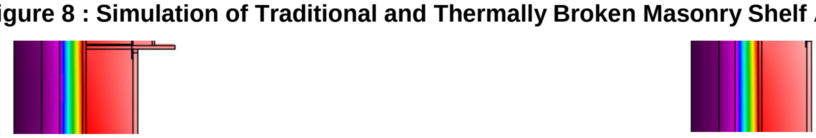


Figure 8 : Simulation of Traditional and Thermally Broken Masonry Shelf Angle



outboard of the insulation, thereby creating intermittent rather than continuous thermal bridges. Providing a thermal break between the brackets and the shelf angle and then conservatively assuming these brackets are spaced at 1,200 mm (48 in.) on center, results in a substantial improvement in performance. In this system we saw only a 12% decrease in the R-Value from the support structure. This could be reduced down to 3% if the blades were made of stainless steel.

In addition to the shelf angle, metal ties are typically required in masonry veneers to provide lateral support. Surprisingly though these installations are intermittent, they occur so frequently that they can have a significant impact on assembly R-values. With typical spacing somewhere between 400 and 600 mm (16 and 24 in.) on center, horizontally and vertically, ties can contribute up to a 15% decrease in the thermal performance. Because spacing, material conductance, and type of tie all impact the R-value for masonry walls, we looked at a matrix of three types of ties: a screw-on tie, a barrel tie, and a thermally-broken tie. We looked at these options at both 400 and 600 mm (16 and 24 in.) spacing in steel and stainless steel. The choice of steel or stainless steel proved to have the biggest impact on performance, with an average of 6% improvement in the R-values, whereas the larger spacing of the ties and the choice of tie type both showed an average of a 4% improvement in thermal performance. Stainless steel ties spaced 600 mm (24 in.) on center, which have minimal diameter of material penetrating the insulation, were shown to have a negligible impact on the thermal performance, decreasing the R-value by only 2%. Combined with the shelf angle held off by the blades, the thermal performance of masonry veneer façades can be improved substantially from the traditional approach.

Insulated Metal Panel Wall Systems

Insulated metal wall panels are popular because they can be a simple and economic strategy for cladding a building. Because the insulation is in integral to the cladding and is sandwiched between two metal skins, the cladding support structure does not act as a thermal bridge. However, we observed that the joints between the panels become critical to maintaining thermal integrity for the system. Due to different approaches to the joints, a large discrepancy was observed in the thermal images between the different options, with some at 60-70% less than the baseline R-value and others at only about 3% thermal degradation.

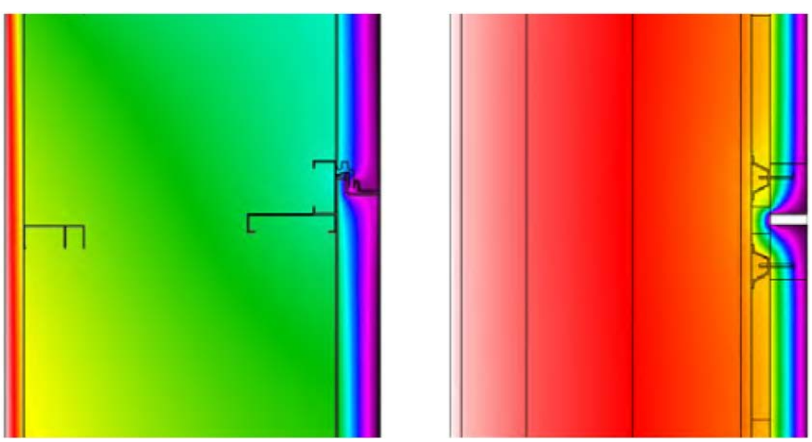


Figure 9 : Metal Panel with Uninsulated and Insulated Joints

The joints were revealed to be the key difference between metal panels that perform poorly and those that performed well. In the poor performing options, the metal front of the panel wraps through the joint, providing a thermal bridge that greatly undermines performance. The façade that performed well, in both the infrared image and the simulation, was backstopped at the gap between connecting panels. The backstop was made of insulation which was wide enough to make a continuous thermal barrier. The simplicity of this joint detail shows how careful detailing can lead to a dramatic improvement in thermal performance.

Curtain Walls

The mullions of curtain walls have long been understood to act as thermal bridges within vision glazing systems. Building codes and other energy standards provide maximum allowable U-values for the whole assembly, accounting for the frame, the edge of the glass that has been de-rated by the frame and the center of glass performance. In most curtain wall buildings, however, this is only part of the installation. Areas between floors and sometimes across the façade are blanked off to create spandrel panels and these are insulated in a variety of ways. However, because the mullions are simply part of the system, few of us really consider the thermal impact the mullions can have circumventing the insulation that has been added. Our thermal images demonstrated that these areas are often substantial sources of heat transfer and the magnitude of the problem is amplified by the density of the mullions and the conductivity of the pieces.

Because curtain wall frames are made of highly conductive aluminum, which is about four times more conductive than steel, and typically go from the exterior of the building through to the interior, they are significant thermal bridges. To combat this, a thermal break in the assembly, which is typically 6 mm (¼ in.) to 25 mm (1 in.) thick and made of a less conductive polyester reinforced nylon, has become a typical component in modern curtain walls. The thermal break is located between the face plate and the structural part of the mullion, the rail, in line with the glazing pocket. This creates a "cold" side for the portion of the frame in front of the glass, and a "warm" side with the structure on the backside. When insulation is added in a spandrel panel, it is most often added along the backside of the panel, between the innermost surfaces of the rails, and is often supported with a metal back pan. The insulation creates a "warm" side and "cool" side of mullion rail and completely disconnects the thermal barrier of the insulation from the thermal break in the frame. In our installations that used this detail, we observed a 70% decrease in thermal performance.

As the industry has progressed over the past few years, we have become savvier. We did have examples of projects where attempts were made to explore alternative approaches to thermal bridges at spandrel panels to minimize the heat lost through the frame. The first option that we looked at included spray foam inserted into the rail in an attempt to create a more insulated structural part of the mullion and continuity between the insulation and the thermal break. As might be expected, this showed little improvement over the same rail filled with air, because the heat is conducted by the aluminum, which is unaffected by the insulation inside the frame. The resulting assembly reflected a 60% decrease in the thermal performance.

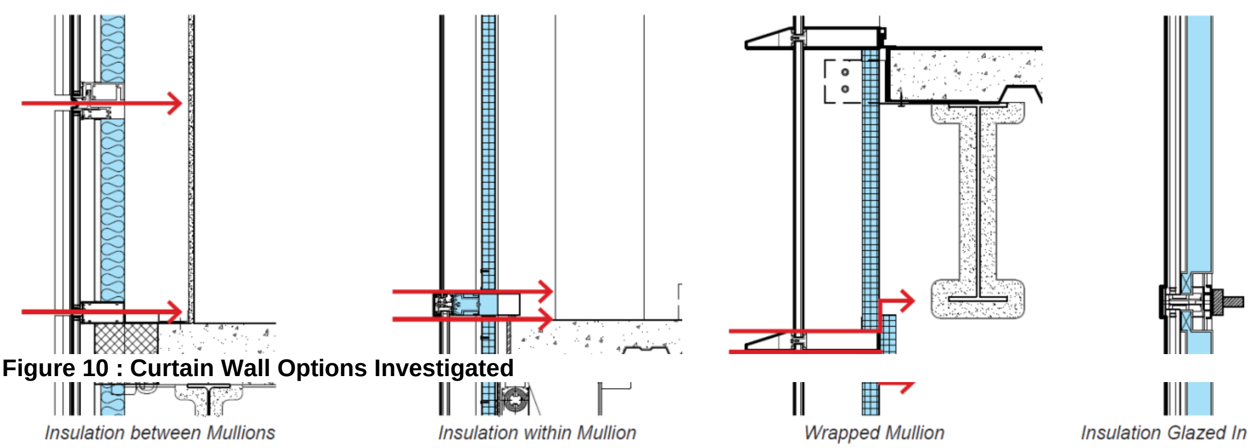
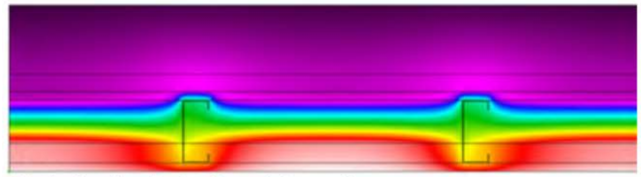


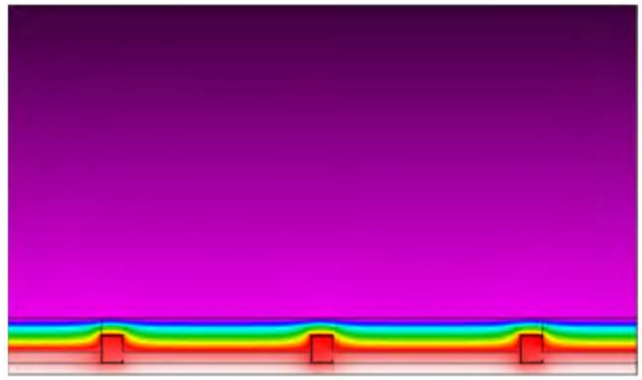
Figure 10 : Curtain Wall Options Investigated

The second alternative added a 50 mm (2 in.) thick by 150 mm (6 in.) tall band of insulation along the back side of the curtain wall rails. This created the promise of a continuous thermal barrier on the backside of the assembly. However, because the rigid insulation is flammable and subject to damage, it included a metal backpan and that was wrapped around the sides and attached to mullion frame. Much like the case of the insulated mullion, the metal pan created a continuous path from warm to cold and though it was very thin, provided an efficient path for heat loss. This too showed a 60% decrease in thermal performance. In our modeling we determined, however, that if the metal pan was removed from the assembly and the insulation could be held in place by a non-conductive material, the theoretical thermal performance decrease could be reduced to only 17%.

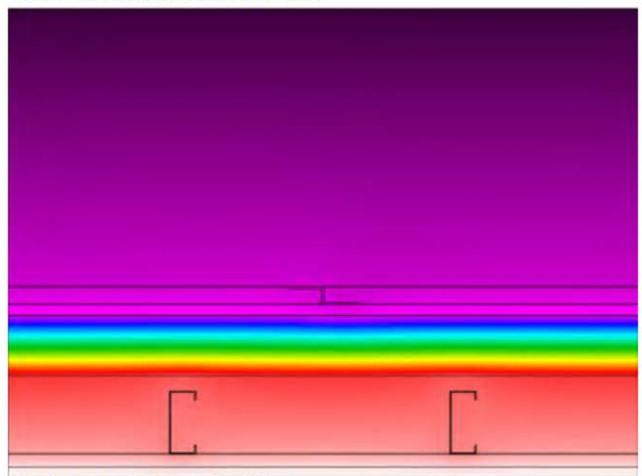
Though it involved a less conventional and more expensive curtain wall, the last detail studied was a structurally glazed steel frame curtain wall with triple glazed insulating glass units. Because this system inherently keeps the mullions in-board of the glass, it restricted thermal bridges. The spandrels saw an approximate 30% reduction in the R-value over theoretical calculations and the spandrels achieved an R_{SI}-2.6 (R_{IP}-15) for the assembly.



Studs directly attached to existing wall
59% of baseline calculated R-value



Studs pulled 1" back from existing wall
16% of baseline calculated R-value



Studs separated from insulation
2% of baseline calculated R-value

Figure 11 : Existing Facade Options Studied

Insulating Existing Buildings

Spray applied insulation is once again gaining popularity, particularly because of its ability to fill unseen voids and provide an integral vapor barrier. In the northeast, it is a particularly popular technology for renovating existing, uninsulated masonry and cast in place concrete facades. Conventional details often call for metal studs to support interior gypsum board and these studs live in the same space as the insulation, creating discontinuities at 400 and 600 mm (16 and 24 in.) on center spacing. While the web of the steel studs is quite slender, they are highly effective heat transfer devices because of the conductivity of the material and the flanges, which provide significant contact area to collect and disperse heat.

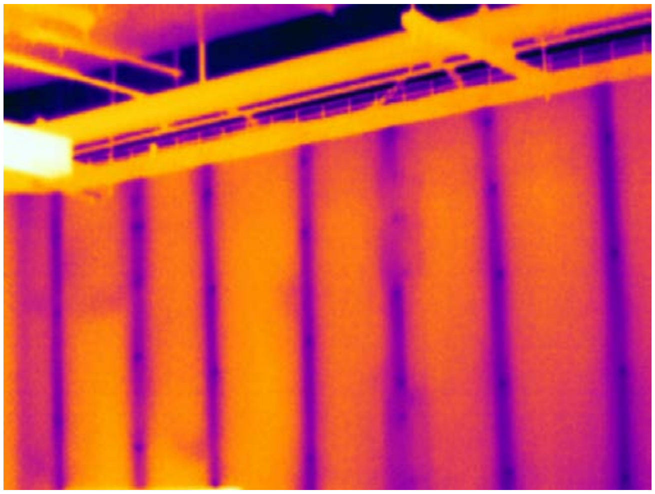


Figure 12 : Infrared image showing studs attached directly to exterior masonry wall

Thermal images of the renovation of three separate existing buildings revealed dramatically different results. The first case, had applied 76 mm (3 in) of insulation, the second employed just 51 mm (2 in.) of insulation, and third used 88 mm (3.5 in.). While hand calculations of the thermal resistance would show the façade with the least insulation to be the weakest performer and the one with the most insulation to be the best, the thermal images revealed a different story. The 76 mm (3 in) of insulation included steel studs flush against the exterior construction, resulting in an R-value that was 55% less than the calculated R-value. The second building pulled the studs back by 25 mm (1 in.), allowing for half of the applied insulation to be continuous which resulted in decreasing the R-value by only 15%. Consequently, that façade was observed to have a higher R-value than one with the studs penetration through to the exterior, despite having less insulation. The third façade took the studs back even farther, completely separating them from the insulation and as a result the simulated R-value was nearly identical to the measured values.

Our study showed that the continuity of the even a small amount of insulation is critical to the efficiency of the spray foam insulation performance. By simply pulling the studs in-board, even by 25 mm (1 in.), to allow a percentage of the insulation to be uninterrupted, the assembly R-value can be increased by about 70%. In the event that the studs are required to support exterior sheathing, it should be possible to fasten the sheathing using discontinuous and non-conductive shims or spacers so that, once again, the majority of the insulation in that outer 1" layer remains continuous. Nevertheless, small changes in the design can still lead to dramatic improvement in performance.

Conclusion

Our research supports the hypothesis that thermal bridging currently has a significant impact in traditionally detailed commercial buildings. Using both thermal imaging and computer-based simulations, we have shown that commonly employed details for transitions in materials, the support of facades, and the installation of windows, can frequently reduce R-values in our assemblies by 40-50% and sometimes well over that. We also found that in some cases, design teams and manufacturers had taken steps to mitigate thermal bridges, but without the proper tools for analysis, had not always succeeded in eliminating problem being addressed. The underlying conclusion we reached was that the design and construction industry has not yet developed an intuitive understanding of thermal bridging. When addressing specific problem details, it is often helpful to confirm our expectations through simplified modeling.

The continuity of a thermal barrier across the entire building envelope is fundamental to good thermal performance. It reduces energy consumption, increases thermal comfort and helps to prevent condensation. It is clear, however, that there are a myriad of other influences such as structural loads, rain, and transparency, which can work at cross purposes to the execution of a perfect thermal boundary. While some conditions may be eliminated, the real goal of our work is to suggest that thermal bridges can be effectively managed and that doing so will have a meaningful impact on the performance of our buildings.

Our research finds that the first priority should be to eliminate continuous conductive elements, such as Z-girts or masonry shelf angles that completely penetrate the insulation layer. These systems are easily interrupted by pulling them outboard of the thermal barrier and using discontinuous supports to make required connections back to structure. Second, try to utilize available thermally broken products to disconnect the heat flow through the thermal barrier. Thermally broken rainscreen support systems, brick ties, and concrete slab connections are readily available and the market is expanding quickly. It is important to note, however that in the application of these products it is essential to ensure the thermal break occurs within the insulation boundary. Our research found some products that are easily foiled by having breaks in undesirable locations relative to the natural placement of insulation. Finally, as a third step, when the thermal bridge is a necessity and structure must penetrate uninterrupted through the insulation, look for materials with the lowest possible thermal conductivity. For example, stainless steel has a third of the conductivity of carbon steel and fiberglass's conductivity is significantly lower than stainless. Materials like Aluminum and Copper are five and eight times more conductive than carbon steel and so these materials should be used in exterior envelopes extremely carefully.

More awareness and education is needed within the building industry on the impact of thermal bridging, so designers become aware of the necessity to focus on careful detailing and specifications to combat them. Additionally, there should be a shift in the discussion from the R-value of the insulation that is specified to the R-value of the assembly as designed. Solely focusing on the number of inches of insulation does not give an accurate picture of the thermal performance of the envelope. Free and accessible tools, such as THERM, are available to assist design teams in the evaluation of complex details that cannot be intuitively understood.

While this study is not intended to be an exhaustive analysis all thermal bridges, it does identify the types of conditions that occur typically and helps quantify their localized impact. While the tested buildings were concentrated in the colder climate of the Northeastern United States, the underlying physics is directly applicable to warm climates and thermal bridges should still be considered serious in areas where there are high summertime outdoor temperatures. More than anything, we anticipate this research helps to develop an intuitive understanding of the situations that lead to the thermal bridging regardless of the specific project conditions, and then provide the tools for easily addressing them.

REFERENCES

ASHRAE. *2009 ASHRAE Handbook Fundamentals.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2009.

ASHRAE. *ANSI/ASHRAE/IESNA Standard 90.1-2007 Energy Standard for Buildings Except Low-Rise REsidential Buildings.* Atlanta, GA: ASHRAE, 2010.

Griffith, Brent, Elizabeth Finlayson, Mehrangiz Yaz, and Dariush Arasteh. "The Significance of Bolts in the Thermal Performance of Curtain-Wall Frames for Glazed Facades." *1998 ASHRAE Winter Meeting.* San Francisco, CA: ASHRAE, 1998.

Lawrence Berkeley National Laboratory. *THERM 6.3 / WINDOW 6.3 NFRC Simulation Manual.* Berkeley, CA: Regents of the University of California, 2011.

Love, Andrea. *Material Impacts on Operational Energy Usage.* Masters Thesis, Cambridge, MA: Massachusetts Institute of Technology, 2011.

Lstiburek, Joseph. *BSI-005: A Bridge Too Far.* Building Science Insights, Building Science Corporation, 2008.

Lstiburek, Joseph. *Thermal Bridges Redux.* BSI-062, Building Science Corporation, 2011.

Madding, Robert. "Finding R-Values of Stud Frame Constructed Houses with IR Thermography." *Inframation 2008 Proceedings vol. 9.* Reno, 2008.

Morrision Hershfield. *Thermal Performance of Building Envelope Details for Mid- and High-Rise Buildings (ASHRAE 1365-RP).* Atlanta: ASHRAE Technical Committee 4.4, 2011.