ASSESSING THERMAL BRIDGES IN COMMERCIAL WALL SYSTEMS

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ABSTRACT

This paper focuses on the methodology developed utilizing the 2-D heat transfer program THERM to more accurately assess the 3-D heat flow from discontinuous bridging elements. Additionally, the research looks at a number of common connection, and compares the calculated U-values to simulation predictions and installed performance using thermal imaging. The paper will focus on both the methodology used, as well as the finding of the research to better comprehend the deviation in thermal performance between design intentions, simulation, and actual performance.

INTRODUCTION

Office towers dominate the skylines of cities all around the world. However, most have been designed with little thought to the climate they are in and the environmental impact they might have. According to a recent government survey, 70% of energy usage in office buildings is from the lighting and HVAC systems (U.S. Energy Information Administration 2008), both of which are directly related to the architectural decisions that have been made in the building form and materials.

One area where architectural decisions have an impact on energy usage is in the envelope of the building. Over the last few years, increasingly stringent energy codes have increased the requirements for building insulation and glazing performance. However, there is a limit to the cost effectiveness of increasing the amount of insulation required without looking at the wall assembly as a whole. As insulation is added to a wall assembly, the thermal bridges typical in most commercial wall assemblies become more dominant as the source of energy loss through the building envelope. Currently there is a push by policy and codes and within practice, such as with the 2030 Challenge and the Department of Energy Building Technologies Program energy saving goals, to develop market-viable net-zero buildings within the next 15-20 years. Better performing building envelopes will be one of the components that will help realize these goals, but to achieve better performance we need to look holistically at the thermal performance of an assembly, rather than just the R-value of the insulation utilized.

With the increasing improvement of insulation requirements in energy codes, thermal bridges represent a larger portion of the heat loss through the envelope. Figure 1 is a theoretical diagram showing the U-value of extruded polystyrene as it varies with thickness and the thermal bridging heat loss found by Lee and Pessiki (Lee and Pessiki 2008). If the thermal short circuit through the insulation still exists as the insulation increases, the value of the heat loss through that thermal bridge does not change with the varied insulation. Currently the energy codes require approximately 8 cm of extruded polystyrene insulation in a cooling climate such as Chicago. As Figure 1 illustrates, at a certain point continuing to increase insulation will provide only a marginal increase in the resistance of the assembly. As the insulation increases, the thermal bridges turn into the dominate source of the heat loss, and minimizing these short circuits of heat flow becomes a more effective strategy to increasing the thermal resistance of the envelope. Given the current insulation requirements and push for higher performing buildings, a greater understanding of thermal bridging in envelopes and its impact on operational energy usage is needed.

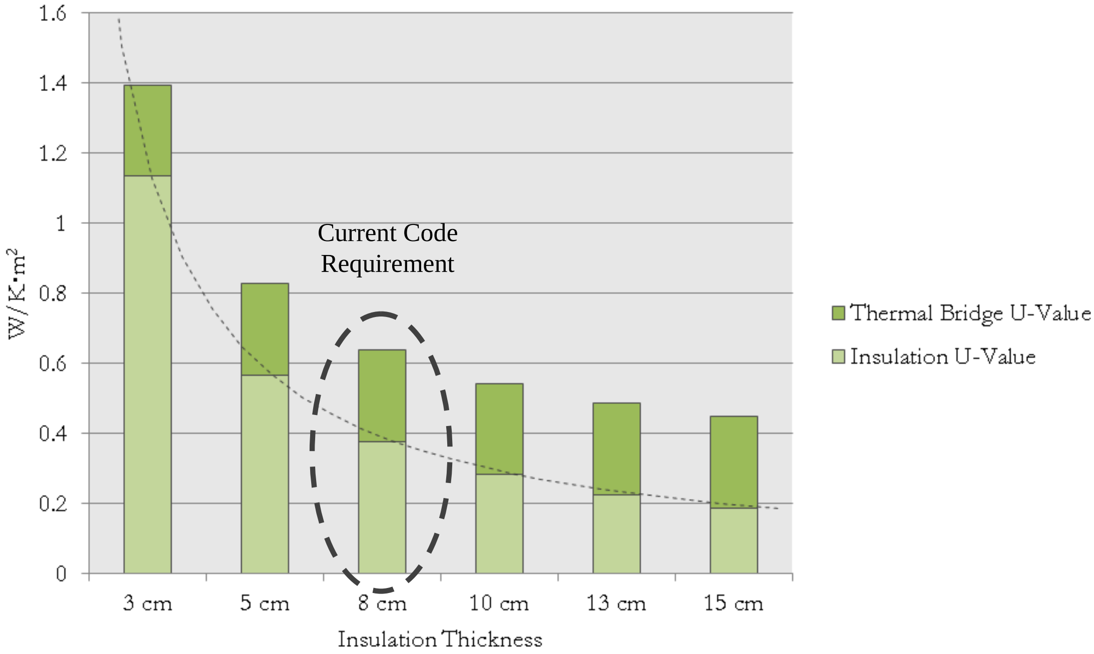

Figure 1: Diagram of Impact of Thermal Bridging on Assembly U-Value as Insulation Increases

CALCULATION METHODOLOGY

Currently available energy modeling software does not accurately account for thermal bridges that may occur from penetrations through the thermal insulation or connections and interface conditions between building components. Because thermal bridges are characterized by multi-dimensional heat flows, energy modeling software, which uses a one-dimensional heat transfer calculation methodology, is unable to assess these conditions. To account for the more realistic thermal performance in an energy model, the clear wall R-value of the assembly can be adjusted to more accurately account for the actual heat transfer. This adjusted value, often referred to as the effective R-value, can be challenging to determine.

To accurately account for the three-dimensional heat transfer occurring in heterogeneous assemblies, a mock-up of the panel can be tested with the guarded hot box method (Evitherm 2011). This test consists of a guard box, meter box, and cold box. A representative sample is fit to the guarded box and temperature and conditions are adjusted on one side, and thermocouples read the surface and air temperature on the resultant side. This method can accurately determine the multi-dimensional heat transfer, but has severe limitations for widespread applications due to its extremely high cost and specialized equipment required. Alternately, a computational simulation can be done using a three-dimensional finite element model, which is a method that utilizes a numerical technique to approximate solutions to complex equations such as partial differential and integral equations. The specialized technical skill and knowledge to create and run these models is beyond that of the typical architectural practitioner, and therefore is an unfeasible method for widespread application in the architecture, engineering and construction industry.

The ASHRAE Handbook of Fundamentals (American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009) outlines alternate, more simplified estimation methodologies for determining the effective R-value of an assembly. The simplest method is the parallel path method, which calculates the heat flow through the clear wall section and the bridge section separately and takes a weighted area average to determine the effective R-value. This method implies that heat flows in parallel paths and does not adjust its direction to find an easier route through the wall. ASHRAE recommends this method as being reasonably accurate for less conductive thermal bridges, such as wood studs in residential walls. However, as the most common penetrations through commercial insulation are metal, this method is not applicable to most commercial wall assemblies.

Building on the parallel path method, the zone method attempts to better account for smaller but more conductive bridges. The zone method determines a zone of influence that is larger than just the width of the bridging member used in the parallel path method. In the zone method, the zone of influence is a function of the width and depth of the construction surface to the conductive element. However, this method has been found to be inaccurate for many types of elements and therefore modifications have been proposed. One adjusted method, also outlined in the ASHRAE Handbook of Fundamentals, is the modified zone method. Based on data from steel stud wall assemblies, this method was developed to more accurately account for the thermal bridging in steel studs. This method amends the formula for determining the zone of influence so that is dependent on a ratio between the thermal resistivity of finish material and cavity insulation, depth and width of stud, and thickness of finish material layers. Likewise, in 2008 Lee and Pessiki proposed a revised zone method for the metal ties in precast concrete sandwich panels, which reforms the equation for determining the zone of influence based on the conductivity of the concrete, insulation and metal tie, as well as the diameter of the tie and the distance from the face of the wall. These adaptations for the zone method illustrate the limitations when applying the zone method to a wide array of applications. The estimation technique was derived for large steel members like beams, however it does not accurately account for discontinuous instances, such as the metal ties, or other unique conditions that may occur in commercial building wall details. Because of this, it has limited application and is not suitable for widespread use with commercial wall systems.

The isothermal plans method, or series-parallel method, divides the construction assemblies into a series of layers. Layers where conductive and insulative elements coexist are handled with a parallel path calculation, but the layers are assumed to have a uniform surface temperature on either side. This method is recommended for wood, concrete and masonry, but not metal, again making it difficult for commercial wall assemblies. Additionally, Zarr et al. found that the isothermal planes method tended to under predict the R-value of wood-framed wall assemblies while the parallel path over predicted it (Zarr 1987).

THERM is a two-dimensional heat transfer program developed by Lawrence Berkeley National Laboratory and is based on the finite-element method (Ernest Orlando Lawrence Berkeley National Laboratory 2011). THERM's simple and easy to use interface is accessible for the average building professional. The program is able to model complex geometries and provides the average U-values and surface temperature for elements. However, the two-dimensional nature of the program was found to be accurate for only elements which are continuous perpendicularly to the section drawn in the program, such as a beam, but highly in accurate for elements that are of shorter depths, such as a bolt.

Griffith et al. (Griffith 1997) describe a method which combines the parallel path method and isothermal planes method with the two-dimensional program THERM to predict the change in thermal resistance from bolts in curtain walls. The parallel path method involves two THERM simulations. The first simulates the wall without the bridging element, and the second simulates the wall with the bridging element. The U-values from the two simulations are then combined by a weighted area average for the areas perpendicular to the sections drawn on the screen:

$$U_P = F_B * UB + F_N * U_N$$

Whereas, U_P = U-value parallel path

F_B = Fraction of bridging element

U_B = U-value from THERM with bridging element

F_N = Fraction of clear wall

U_N = U-value from THERM of clear wall

The isothermal planes method requires only one simulation, but requires an effective conductivity to be calculated prior to the simulation. The effective conductivity is calculated by a weighted area average of the conductivity of the bridging element and insulative element, and this value is then used for the bridging element during simulation:

$$k_{eff} = F_B * k_B + F_N * k_N$$

Whereas, UI = U-value from THERM using isothermal planes method

k_{eff} = effective conductivity

k_B = conductivity of bridging element

kN = conductivity of non-bridging element

The study compared the temperature and U-value results to the measured temperature results from a guarded hot box test. Since the U-value is the overall heat transfer coefficient, the resultant surface temperature is directly proportional to the U-value. As show in Table 1, the parallel method tended to underestimate the heat flow, while the isothermal planes method over-estimates the heat flow. However, when the two results are averaged as shown in Table 1, the discrepancy from the measured experimental temperature is on average within 3.5%, and all values were well within 10 percent.

Table 1: Average Surface Temperature Results Comparision (Griffith 1997)

	MEASURED	PARALLEL PATH		ISOTHERMAL PLANES		AVERAGED	
	°C	°C	% DIFFERENT	°C	% DIFFERENT	°C	% DIFFERENT
Nylon, 229mm	12.4	11.5	-7.3%	11.5	-7.3%	11.5	-7.3%
Stainless,457mm	11.0	11.3	+2.7%	10.5	-4.5%	10.9	-0.9%
Stainless,305mm	10.8	11.2	+3.7%	10.1	-6.5%	10.7	-0.9%
Stainless,229mm	10.7	11.1	+3.7%	9.8	-8.4%	10.5	-1.9%
Stainless,152mm	10.5	10.9	+3.8%	9.2	-12.4%	10.1	-3.8%
Stainless, 76mm	9.4	10.3	+9.6%	7.9	-16.0%	9.1	-3.2%
Steel, 229mm	8.8	11.1	+26.1%	7.7	-12.5%	9.4	+6.8%
Average			±8.1%		-9.7%		± 3.5%

Validation Example

For this reason, the decision was made to use the averaged value from both the THERM parallel path and THERM isothermal planes methods described by Griffith (Griffith 1997). To validate this methodology, a sample was calculated for an M-tie in a concrete sandwich panel with 51 mm of insulation between 76mm of concrete and spaced 610 mm on center, shown in Figure 2, using the revised zone method (Lee and Pessiki 2008).

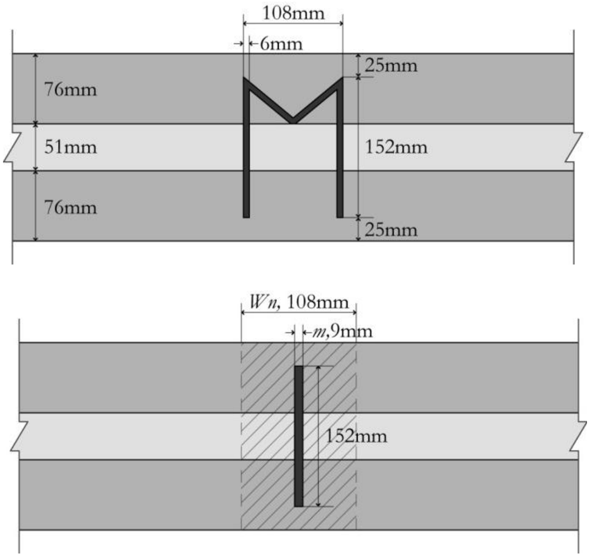

Figure 2: Section of the M-Tie Metal Wythe and Simplified Equivalent Bar

The conductivity, k, of the materials is assumed to be:

kcon = 1.92 W/m°K for concrete

kin = 0.029 W/m°K for insulation

kct = 45.3 W/m°K for metal Wythe

The two legs can be combined into one leg, and the diameter of the equivalent bar, m, is defined to be:

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Witdth identified as the distance from the panel surface to the connector, the width of the zone of influence is defined to be:

$W_n = (0.174k_{con} - k_{in} + 0.0026k_{ct} + 2.24)\ m + 0.02k_{con} - 0.6k_{in} + 0.0024k_{ct} + 2.35 - 0.15d = 125\text{mm}$

The area of influence, Zone A, is the area of the circle which is circumscribed by the diameter W_n, and therefore is 12,300 mm. Since the ties are spaced 610 mm on center, a 610 mm by 610 mm section with the tie in the center can be evaluated to be representative of the whole wall, because at the center line between the two ties the heat flow is symmetrical. Therefore, the clear wall zone, Zone B, is the difference between the area of the section investigated and Zone A, which is 359,300 mm^2. Zone A consequently represents 3.3% of the area and Zone B 96.7%. The U-values are then calculated independently for each zone in Table 2 and Table 3. Within Zone A, the equivalent bar represents 0.5% of the area.

Table 2: Zone B U-Value Calculation

	K (W/M °K)	WIDTH (M)	U = K/T (W/M2° K)	R VALUE (M2°K/ W)
Outside Surface	NA	NA	33.40	0.03
Concrete	1.92	0.076	25.23	0.04
Insulation	0.029	0.051	0.57	1.76
Concrete	1.92	0.076	25.2	0.04
Inside Surface	NA	NA	8.35	0.12
			$U_T = 1/\Sigma R$	$R_T = \Sigma R$
Combined Assembly			0.50	1.99

* NA – not applicable

Using the revised zone method, the Zone A U-value is found to be 2.39 and the Zone B U-Value of 0.50, which when combined with a weighted area average and is equal to 0.56. This was then compared to the THERM parallel path simulations and averaged with the THERM isothermal plane simulations using the same conductivity as the ones used in the revised zone method calculations. The effective conductivity, k_{eff}, was calculated to be:

F_B = Diameter of M-tie/Height of Section = 6mm/610mm = 0.01

$F_N = 1\text{-}F_B = 0.99$

$k_{eff} = F_B * k_{ct} + F_N * k_{in} = (0.99) * (0.029) + (0.01) * (45.3) = 0.50$ W/m°K

Table 3: Zone A U-Value Calculation

	A_F, FRACTION	K (W/M°K)	WIDTH (M)	$U = A_F \cdot K/T$ (W/M²°K)	$R=1/\Sigma U$ (M²°K/W)
Outside Surface	NA	NA	NA	33.40	0.03
Concrete	1	1.92	0.025	75.71	0.01
Concrete	0.995	1.92	0.051	37.65	0.02
M-Tie	0.005	45.3	0.051	4.46	
Insulation	0.995	0.029	0.051	0.56	0.20
M-Tie	0.005	45.3	0.051	4.46	
Concrete	0.995	1.92	0.051	37.65	0.02
M-Tie	0.005	45.3	0.051	4.46	
Concrete	1	1.92	0.025	75.71	0.01
Inside Surface	NA	NA	NA	8.35	0.12
				$U_T = 1/\Sigma R$	$R_T = \Sigma R$
Combined Assembly				0.42	2.39

* NA – not applicable

The results from the three THERM simulations are shown in Figure 3. The color bands represent temperature ranges within the assembly, with the white being the interior temperature and purple the exterior temperature. When all of the color bands and grouped together in the insulation, little thermal bridging is occurring, however, when the range of color bands decreases between the interior and exterior surfaces a thermal short is occurring.

The results from the three THERM simulations are shown in Table 4. The color bands represent temperature ranges within the assembly, with the white being the interior temperature and purple the exterior temperature. When all of the color bands and grouped together in the insulation, little thermal bridging is occurring, however, when the range of color bands decreases between the interior and exterior surfaces a thermal short is occurring.

Table 4: Revised Zone Method Calculation and Proposed Simulation Method Comparison

	WALL FRACTION	U-VALUE (W/M²°K)	DIFFERENCE FROM CALCULATED
Calculated	1	0.56	-
Parallel Path, Clear Wall	0.99	0.51	-
Parallel Path, M-Tie	0.01	2.43	-
Parallel Path, Combined	1	0.53	-7.0%
Isothermal Planes	1	0.64	+12.5%
Averaged U-Value	1	0.58	+2.8%

The results of the validation test showed that the averaged U-values more closely fit with the calculated U-value. Both of the results were within 15% of the calculated value, but the averaged value was shown to be with 3%, which is consistent with the range seen in the study by Griffith et al. shown in Table 1. Although the revised zone method is an estimation of the heat flow, it was derived from finite element models and guarded hot box tests, so it is considered to be reasonably accurate. The ability to utilize the proposed methodology with THERM allows for quicker study of more complex details that otherwise may be impossible to calculate accurately with existing methods

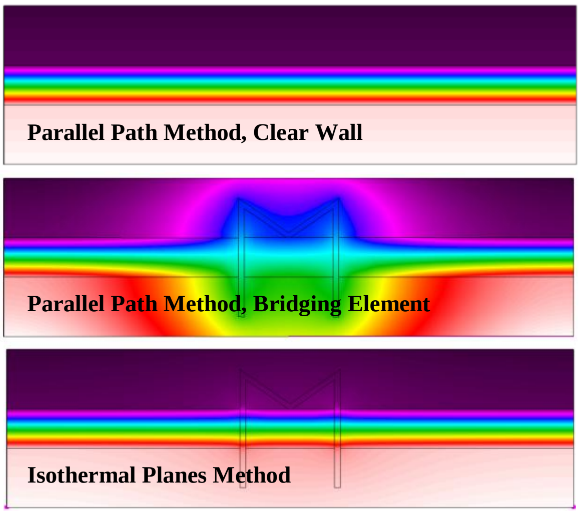

Figure 3: THERM Results for Parallel Path and Isothermal Methods Simulations

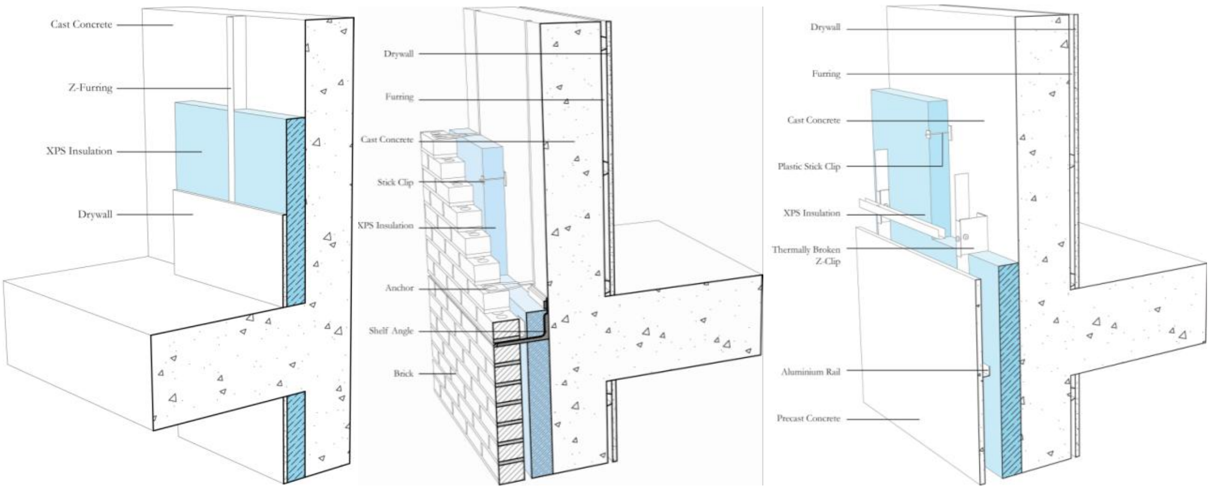

Figure 4: Axonometric of the Connection Details for the Cast-in-Place Concrete Wall with Interior Insulation, Exterior Insulation with a Masonry Façade, and Exterior Insulation with a Thermally Broken Rain Screen

WALL SYSTEMS INVESTIGATED

A series of representative concrete and stick built wall systems were choosen to investigate a range of thermal bridging impact. Selected commercial building wall systems were varied to understand range of thermal bridges. The study was not intended to be a comprehensive catalog of thermal bridges, nor are thermal bridges a condition unique to concrete or stick-built wall systems, as they occur in nearly every commercial building envelope system. Although many layers exist in wall assemblies, only those which influence conductive heat transfer were included and elements such as vapor barriers and paint were excluded. The study is intended to represent a sample of façade systems inorder to estimate the heat loss to better understand how that may impact a building's energy usage and carbon emissions.

The clear wall U-value was first calculated for each assembly. Wall assemblies which have multiple bridges occurring were evaluated in stages. The smallest bridge was examined first, and the heat loss through that bridge was determined. This was then used to adjust the insulation R-value to account for the additional heat loss from the first thermal bridge. This adjusted value was then used as the starting point for the next thermal break evaluated, and the process was continued in a cumulative fashion.

For areas where heat is lost through the slab and ceiling, as well as the wall, the U-value is taken from the exterior surface in THERM to account for all heat flow through all three surface of the a space.

Concrete Wall Systems

While historically many concrete walls did not install insulation, current energy codes now require all mass walls to have insulation in all climates except Climate Zone 1, which covers only the southern tip of Florida and Hawaii. An easy and affordable way to attach the insulation and finishes is with Z-furring strips, because they can serve both as the attachment for the insulation as well as the furring strip for a drywall finish, as shown in Figure 4. A sensitivity study was done both with and without the bolts in the furring, and the difference was found to be negligible.

Due to the large amount of heat lost through the slab from having the insulation on the interior, a system was looked at that would allow for a more continuous insulation system on the exterior. However as insulation needs an exterior finish for protection, such as a brick veneer shown in Figure 4, the structural ties for this system typically cause thermal bridges. This requires connections back to the concrete wall system for structural support. Additionally, fasteners, such as stick-clips, are needed to secure the insulation to the concrete wall. These structural connections and fasters all cause thermal shorts in the insulation.

Because continuous metal penetrations through the insulation are known to cause substantial thermal bridges, new systems have arisen which aim to break these thermal shorts. One such system is thermally broken Z-clips, which are two angles with thermal spacers between the angles. Although, the bolts still penetrate through, this connection minimizes the continuous metal heat flow path by separating the two angles with the thermal spacer. Though the stick clip did not represent a significant thermal bridge, plastic stick clips are also available which have a greater resistance to heat flow. The thermally brocken rain screen wall shown in Figure 4 was intended to represent a wall with more careful consideration given to the detailing of the thermal envelope, and has a precast concrete panel rain screen system on the exterior.

As can be seen in Table 5, there can be a significant range in the impact the detailing of connections can have on the assembly's R-value. While all the systems investigated did still have thermal bridges reducing the assemblies R-values, the attention paid to how the wall is detailed in design can have a significant impact on the perfomance of the façade.

Table 5: Results of Simulation Runs for the Concrete Wall Systems

	R-VALUE (M^{2}°K/W)	DIFFERENCE FROM CALCULATED
Concrete Wall with Interior Insulation		
Calculated Center of Cavity	3.00	-
Z-Furring, THERM	1.76	- 41%
Slab & Z-Furring, THERM	1.03	- 66%
Concrete Wall with Exterior Insulation and Masonry Façade		
Calculated Center of Cavity	3.00	-
Stick Clip, Parallel Path	3.00	0%
Stick Clip, Isothermal Planes	2.94	- 3%
Stick Clip, Combined	2.97	- 2%
Stick Clip & Anchor, Parallel Path	2.55	- 15%
Stick Clip & Anchor, Isothermal Planes	2.24	- 25%
Stick Clip & Anchor, Combined	2.40	- 20%
Stick Clip, Anchor, & Shelf Angle, THERM	1.80	- 40%
Concrete Wall with Exterior Insulation and Thermally Broken Rain Screen		
Calculated Center of Cavity	3.00	-
Plastic Stick Clip, Parallel Path	3.00	0%
Plastic Stick Clip, Isothermal Planes	2.99	0%
Plastic Stick Clip, Combined	3.00	0%
Stick Clip & Thermally Brocken Z-Clips, Parallel Path	2.58	- 14%
Stick Clip & Thermally Brocken Z-Clips, Isothermal Planes	1.94	- 35%
Stick Clip & Thermally Brocken Z-Clips, Combined	2.26	- 25%

Stick Built Wall Systems

Stick built walls are a common backup wall system in commerical envelopes. Historically, insulation was placed between the metal studs, however with the increasing emphasis on the thermal performance of the building envelope, exterior insulation has become the norm in the construction industry. As with the concrete wall systems, three stud wall constructions were investigated to understand the range of the impact the thermal shorts might have on the assembly's R-value. In addition the the thermal simulations, the R-values of the assemblies were also looked at with a thermal imaging camera to provide a better understanding between the design intented R-value, the simulated R-value, and how the assebly performances when constructed. The R-values from the thermal images were calculated using the method described in Madding (2008).

The first system investigated was a fiber reinforced cemetious panel (FRCP) rain screen system. This system was designed with continuous Z-furring to support the rain screen. Additionally, the design contained gaps in insulation at intersections between building components such as the blocking at roof and wall connection detail shown in Figure 5. Both the Z-furring and blocking provide significant thermal bridges.

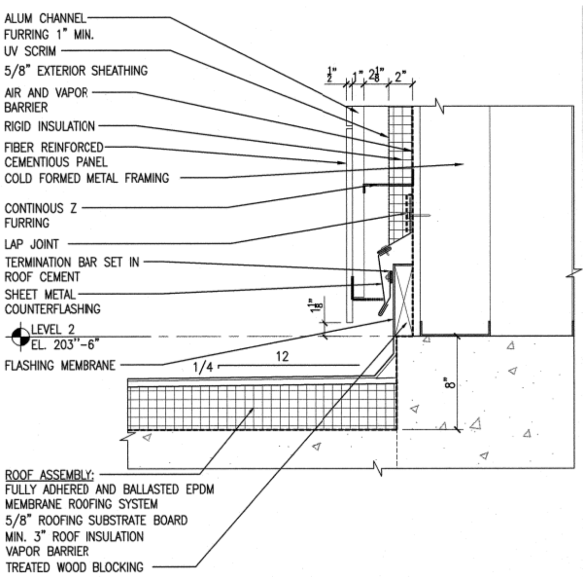

Figure 5: Construction Detail of FRCP Rain Screen Panel at the Slab Edge

Table 6: Table of Calculated, Simulated and Measure R-value of Stick Built Wall Assemblies

	CLEAR WALL R-VALUE ($m^2°K/W$)	**SIMULATED R-VALUE ($m^2°K/W$)**	**DIFFERENCE FROM CALCULATED**	**THERMAL IMAGE R-VALUE ($m^2°K/W$)**	**DIFFERENCE FROM CALCULATED**
FRCP Rain Screen	2.49	0.86	- 65%	0.66	- 73%
Terra-cotta Rain Screen	2.49	1.47	- 41%	1.12	- 55%
Metal Panel	3.63	3.58	- 1%	3.41	- 6%

The next next wall system that was looked at was a terra-cotta rain screen. Similar to the FRCP wall system, Z-girts were used to support an exterior terra-cotta rain screen. More careful attendtion was paid in the detailing of the wall system to minimize thermal bridging at connection points in the assembly, however as with the furring, the Z-girts still significantly reduce the thermal performance of the assembly.

The last wall system was a metal panel system, which integrates the insulation within the exterior cladding. While the connectors between the panels provide the possibility of a thermal short to occur, attention was paid to the detailing of the assembly, as can be seen in Figure 6 which minimizes any breaks in the envelope's thermal barrier so that the connector bolts in the panels are the only potential thermal bridges.

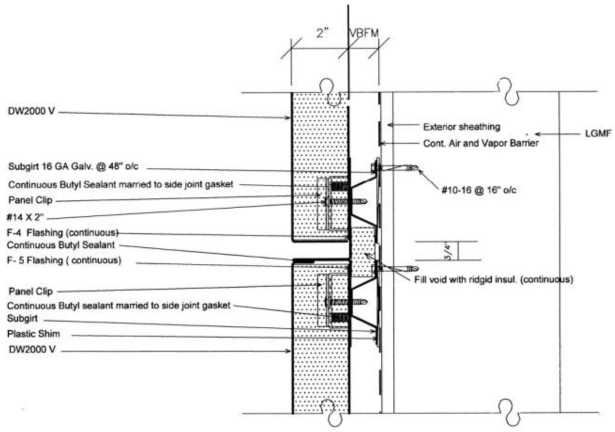

Figure 6: Construction Detail of Metal Panel Connection

As with the concrete wall systems, the thermal bridging stick built wall systems studied had a large range of impact, where some systems showed little difference between the calculated clear wall R-value and the R-value determined thorugh the simulation and thermal imaging, whereas other wall designs showed dramatic decrease in performance from the thermal bridges.

While the R-values from the thermal image and the R-vlaues from the simulations did not always closely align, this is likely due to a number of factors like the differences between realworld and idealized simulations conditions, additional thermal bridges or other conditions that may not have been accounted for in the simulation, or difficiencies and changes that may occur during the construction process. However, the results do correlate between the thermal images calculations and simulations, but further analysis and comparision is needed to better understand the discrepecies.

CONCLUSION

Thermal bridging occurs in almost all commercial wall systems, but only limited research has been conducted on it thus far. Furthermore, methodologies to accurately assess heterogeneous wall assemblies have severe limitations. From the evaluation conducted, a method has been proposed that is accessible to architects utilizing the two dimensional heat flow software THERM and the parallel path and isothermal plane estimation methodologies. A sample of wall assemblies were evaluated representing a range from envelopes that were carefully thermally detailed to those where thermal concerns were not likely considered. The consideration and attention given to connections and how the building envelope is constructed caused a large range in the resulting R-values.

This investigation of thermal bridging in building envelopes is by no means exhaustive, and many other thermal conditions exist. Additionally, this study looked primarily at bridging within a wall assembly, neglecting areas where the wall interfaces with other systems such as parapet and roofs, foundations, windows and doors. Thermally imaging has shown these conditions are likely to further increase the thermal shorts that may occur, and additional research is needed. Though large thermal bridges were seen in some of the assemblies, these could be larger with poor detailing or construction of these interfaces. Instead, this envelope investigation establishes an understanding of some of the range of thermal bridges that exist and propose a methodology for further investigation.

It is important to focus on minimizing thermal breaks as small building improvements can coalesce into larger ones when strategies are combined to reduce energy usage and carbon emissions. A high performance building envelope should be a key strategy for any high performance building, and we have reached the point where minimizing thermal bridges can have more of an impact of envelope performance than just increasing the amount of insulation. However, further study is needed of more wall systems to better understand thermal bridges in commercial wall systems and how they can be minimized.

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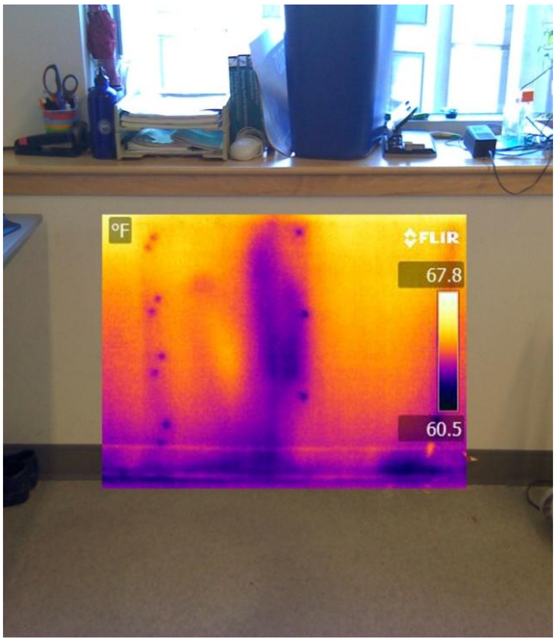

Figure 7: Thermal Image of FRCP Rain Screen Wall System

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