THERMAL PERFORMANCE OF THREE-DIMENSIONAL BUILDING ENVELOPE ASSEMBLIES AND DETAILS FOR IMPROVING THE ACCURACY OF WHOLE BUILDING PERFORMANCE SIMULATION

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ABSTRACT

Thermal bridging through insulation layers in the building envelope reduces the thermal performance of building envelope assemblies and heat flow through thermal bridging can have a detrimental impact on whole-building energy performance. So, it is important for energy modelers, building engineers, and architects to consider the effects of thermal bridging when evaluating the expected performance of building envelope details and when designing building envelopes for energy efficient buildings. However, it is difficult to determine how much heat flows through thermal bridges using typical approaches, such as the area-weighted average of U-values, especially when dealing with three-dimensional (3D) heat flow paths.

In ASHRAE Research Project 1365 (RP-1365), a methodology was developed, using a calibrated 3D model, that enables designers to account for heat flow through thermal bridges in a simple and practical manner. This approach can improve the accuracy of whole building performance simulations where complex thermal bridging is often ignored. This paper will provide an overview of RP-1365 and its potential impact on energy simulation. The impact on whole building energy performance will be examined for three building types in four different climates.

INTRODUCTION

Building owners and operators are increasingly demanding that more attention be paid to reducing building energy use. Although total building energy use is of most concern, reduction efforts are often focused piece-meal on individual building systems. With regards to the building envelope, building regulators have responded by steadily increasing the thermal performance requirements in energy codes and standards over the last twenty years. Designers have typically met these building envelope requirements by adding more insulation, with little attention being paid to thermal bridging.

Standard practice in North America to account for thermal bridging within the building envelope is to consider thermal bridging within an assembly, for example a steel stud wall, but to ignore thermal bridging at architectural and structural details—including interfaces—where walls, windows, floors, and roofs come together. Whole building energy modeling procedures for performance based compliance in many North American energy codes and standards are either largely silent on thermal bridges relating to details (such as, slab edges, shelf angles, and flashings), or they allow these thermal bridges to be ignored through partial or full exemptions, or the procedures reduce the apparent significance of thermal bridges through oversimplification. The reasons for these omissions appear to be based on:

- The belief that details do not have a significant impact on the overall building envelope performance and on whole building energy use because they comprise a small area compared to the total envelope area.
- Past experience that shows it would take too much effort to quantify all thermal bridges, which often have complex three dimensional (3D) heat flow paths.
- The lack of comprehensive thermal transmittance data for standard details.

Accounting for heat flow through details has shown that the overall performance of many common wall assemblies is much less than what is currently assumed by many practitioners (Morrison Hershfield Ltd. 2011). Irrespective of the small areas of highly conductive materials that bypass the thermal insulation, the effect on overall energy consumption is significant, and simple changes to assembly design may be more effective at reducing energy use than adding more insulation. In addition, accounting for these details is now easier because straightforward procedures to quantify the impact of common details have been developed and thermal transmittance data for standard details are now readily available. Realistic expectations of building envelope performance are necessary to make informed decisions related to building energy efficiency.

This paper utilizes the procedures and data developed in the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) research project 1365 (RP-1365), *Thermal Performance of Building Envelope Details for Mid- and High-Rise Construction,* to show how easily the impact of all thermal bridging can be integrated into the overall thermal performance of the building envelope and into whole building energy simulations. Examples are provided to demonstrate the impact that building envelope details can make on the overall building envelope performance, building space heating energy, and whole building energy use for multi-unit residential buildings and offices in four different climates.

CURRENT PRACTICES IN ACCOUNTING FOR THERMAL BRIDGES

The typical practice in North America to calculate the thermal performance of assemblies and details is to use an area-weighted average. This approach blends all the effects of the thermal bridges with the rest of the wall or roof by considering them all as one entity. Typically this is done by weighting the heat flow through the materials by the area they take up (which assumes that there is no interaction between materials) or by component modeling an assembly and averaging the heat flow over the area of influence of the thermal bridge. However, area-weighting has two major drawbacks.

While areas may be easily determined for large plane assemblies like windows or typical wall assemblies, the areas of influence of details like slab edges, parapets, and window transitions are much more difficult to define because lateral heat flows, like those shown in Figure 1, complicate the process. The effective lengths—the length where a thermal bridge has influence on a wall assembly—can be drastically different depending on the starting point of the analysis. This can lead to lengthy calculations and arbitrary definitions of the areas of influence, which can reduce the accuracy of the results. This breaks down even further when the adjacent assemblies have complex heat flow paths due to thermal bridging in three dimensions. For example, ASHRAE PR-1145, *Modeling Two and Three-Dimensional Heat Transfer through Composite Wall and Roof Assemblies in Hourly Simulation Programs*, requires at least five equations to calculate the overall transmittance of a simple building using the area-weighted method (Enermodal Engineering Ltd 2001).

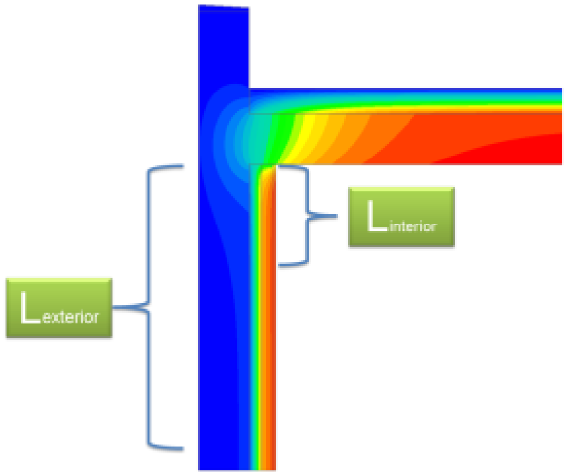

Figure 1 Effective lengths for area-weighted calculations for parapet from exterior and interior

The other major drawback to area-weighting is that it is harder to quantify the individual contribution of a single thermal bridge because the effects are averaged over the entire area, diluting the impact of the thermal bridge with the heat flow in the field of the wall clear of thermal bridges. For example, the area-weighted heat flow at a slab detail will appear to have less of an effect on a wall with a 12-ft ceiling height than a on a wall with a 9-ft ceiling height, making it harder to appreciate where the larger contributions to the heat flow are. For these reasons it is difficult to use the area-weighting method to calculate thermal values consistently and to apply them generically for practical use beyond a single project.

ASHRAE RP-1365 AND THE METHOD OF LINEAR TRANSMITTANCE

ASHRAE Research Project RP-1365

ASHRAE RP-1365 was initiated to address the uncertainty related to the thermal performance of the building envelope, which can lead to inefficient design of HVAC systems, inefficient building operation, inadequate condensation resistance at intersections of components, and compromised occupant comfort. The objective of ASHRAE RP-1365 was to provide thermal performance data of 40 common building envelope details for mid- and high-rise construction. The goal of the project was to develop procedures and a catalogue that will allow designers quick and straightforward access to information but with sufficient complexity and accuracy to reduce uncertainty in evaluating the thermal performance of building envelope components.

Modeling for this project was done using a three-dimensional finite element analysis heat transfer software package by Siemens PLM Software, FEMAP and Nx, with Maya HTT Ltd's TMG-Thermal solver. The model was validated with ISO standards and guarded hot-box test measurements, with good agreement between simulated and measured thermal performance for both steady-state and transient conditions. Details are provided in Chapter 3 of RP-1365.

The method of linear transmittance

A key finding of RP-1365 was that applying an area of influence to a spectrum of thermal bridges, considering 3D heat flow, cannot be done with consistency, is overly complicated, and in many cases is arbitrary. ASHRAE RP-1365 employed the method of linear transmittance to characterize thermal bridging in details to overcome the drawbacks in the area-weighting method.

Instead of trying to find areas of influence, this approach takes the "additional" heat flow due to a thermal bridge and assigns it to simple mathematical construct of lines or points. An example of the simplified process for a floor slab through a wall is shown in Figure 2.

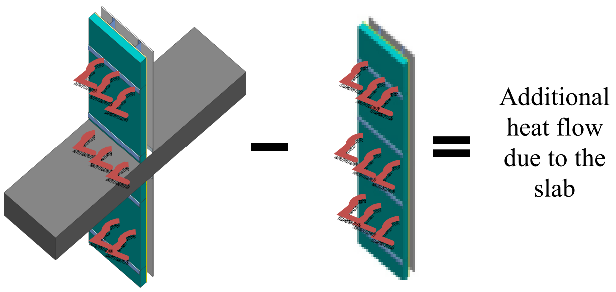

Figure 2 Determining linear transmittance for a slab

The additional heat flow caused by a thermal bridge is the difference between the heat flow from an assembly with and without the detail present. This approach allows thermal bridging in details to be treated separately from the wall or roof assemblies. It simplifies calculations because the areas of the thermal bridges are not required. Calculations involve adding up these linear and point transmittances to find the heat flow through the details. They can also be added to the heat flow through the assembly to find the overall heat flow through the opaque building envelope. In this approach, all thermal transmittances are grouped into three categories: clear field transmittance, linear transmittance, and point transmittances. Examples of each are shown in Figures 3, 4, and 5, respectively.

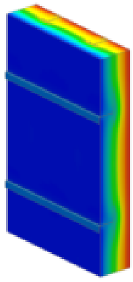

Figure 3 Example clear field transmittance assembly

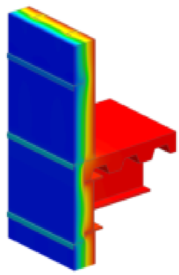

Figure 4 Example linear transmittance detail

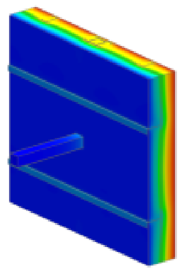

Figure 5 Example point transmittance detail

The clear field transmittance is the heat flow from the wall or roof assembly, including uniformly distributed thermal bridges that are not practical to account for on an individual basis, such as light gauge steel framing, brick ties, and cladding supports. Clear field transmittance is the same as the customary U-value, that is, heat flow per area, except it is represented by U_o. For a specific area of opaque wall, clear field transmittance can be converted into an absolute heat flow Q_o.

The linear transmittance is the additional heat flow caused by details that can be defined by a characteristic length, L. For example, details with linear transmittance include slab edges, corners, parapets, and transitions between assemblies. The linear transmittance is a heat flow per length, and is represented by psi (Ψ).

The point transmittance is the heat flow caused by thermal bridges that occur only at single, infrequent locations. This includes building components such as pipe penetrations and intersections between linear details. The point transmittance is a single additive amount of heat, represented by chi (χ).

Calculating thermal performance using linear and point transmittances

Since linear and point transmittances are separate from the clear field, they can be evaluated on their own. This way, details can be directly compared for thermal performance. This also means that, since they are separate, linear or point transmittances that have already been calculated can be used in the overall wall or roof calculations without having to remodel the assemblies for differences in building dimension. Since linear and point transmittances are quantities of additional heat flow, the overall heat transfer of the exterior surface is just a simple addition process as shown in Equation 1:

$$Q = \Sigma\, Q_{thermalbridge} + Q_o = \Sigma\,(\Psi \cdot L) + \Sigma\,(\chi) + Q_o \quad (1)$$

Where:

Q = Overall heat flow from the wall or roof including all thermal bridges (Btu/hr·°F or W/K).

$Q_{thermalbridge}$ = the additional heat flow caused by major thermal bridges (Btu/hr·°F or W/K).

Q_o = Heat flow from the clear field assembly (Btu/hr·°F or W/K).

Ψ = Heat flow from linear thermal bridge (Btu/hr·ft·°F or W/m·K).

L = Characteristic length of linear thermal bridge (ft or m).

χ = Heat flow from point thermal bridge (Btu/hr·°F or W/K).

The overall heat flow through the wall or roof, Q, is the summation of all of the thermal bridges plus the clear field heat flow. There can be many different types of linear and point transmittances but they are all included in the final overall heat flow. For this calculation, L is the characteristic length of the linear thermal bridge. For a slab edge, this would be the length the details occur across the face of the building. By finding the heat flows separately, each component can be evaluated to find their relative contribution to the overall heat flow. By looking at the relative contribution of each component of the envelope, designers can prioritize where to expend design effort—a limited resource—in improving the details that will yield the greatest reduction in heat flow.

Equation 1 gave the overall heat flow for a building of a particular size. In order to be more useful for energy modeling, the overall heat flow rate through the wall or roof is typically presented as a U-value. Knowing U=Q/A, Equation 1 can be converted into Equation 2:

$$U = \frac{\Sigma\,(\Psi \cdot L) + \Sigma\,(\chi)}{A_{Total}} + U_o \quad (2)$$

Where:

U = Overall effective wall thermal transmittance (Btu/hr·ft^2·°F or W/m^2·°K).

U_o = Clear field thermal transmittance (Btu/hr·ft^2·°F or W/m^2·K).

A_{Total} = Total opaque wall area (ft^2 or m^2).

While this method could be applied to fenestration, the analysis of fenestration products is already well established in the North American building industry (NFRC 2010). Since fenestration and opaque walls are typically dealt with independently, there is no conflict between using the linear transmittance with the opaque wall sections alongside other conventional heat flow methods for fenestration.

ASHRAE RP-1365 thermal performance catalogue

Once a linear (Ψ) or point transmittance (χ) has been calculated for a particular detail, it can be used with any building that includes the same wall type and detail in design. Consequently, catalogues for thermal performance values for various details can be made and used, as a reference, for calculations without needing to thermally model them every time. This makes it convenient for practical use to determine the overall transmittance of the opaque building envelope.

ASHRAE RP-1365 provides a catalogue of 40 common details found in mid- and high-rise construction for several types of assemblies. They include steel stud assemblies with various cladding attachments for exterior or split insulation, concrete mass walls, precast concrete walls, brick veneer assemblies, and the opaque portion of curtain wall assemblies. The details include various slab edges, parapets, window transitions, and beam penetrations. The catalogue provides clear field, linear, and point transmittances for varying amounts of exterior insulation (depending on the assembly type). The catalogue also provides temperature indices so that designers can quickly determine surface temperatures and evaluate the risk of condensation in a particular detail.

The linear transmittances can also be divided into ranges, essentially fitting into poor, average, and efficient in terms of thermal performance. For example, the linear transmittance for an un-insulated balcony slab would be in the high range (or "poor"), a partially insulated slab edge with a metal flashing would be in the medium range (or "average"), and a fully insulated slab face would be in the low range (or "efficient"). Examples for these linear transmittance ranges are shown in Table 1.

These ranges are useful for preliminary design, where specific details have not yet been chosen. For instance, an initial linear transmittance for the slab edges in a building design could be assumed in the poor range. A preliminary energy model may show that there could be large energy savings in improving the slab edge detail. A low transmittance slab edge detail considered to be in the "efficient" range could then be chosen for the design. These ranges can also provide guidance for estimating the thermal performance of details that are not in catalogue and without having to explicitly model them. With some judgment, a particular detail can be compared to a similar detail in the catalogue and estimated whether it is likely to have a better or worse thermal performance.

The amount of additional heat flow will also depend on the frequency of details. On a multi-storey building an "efficient" slab detail with a low linear transmittance may contribute significantly more to the overall heat flow than a "poor" parapet detail with a high linear transmittance because the slab detail occurs at every floor whereas the parapet details only occurs at the roof.

Using linear and point transmittances in practice

The following example illustrates the practical use of the linear and point transmittance approach. Take a single elevation of building with an R-20 exterior and R-13 interior split insulated steel stud assembly, as shown in Figure 6, with the building parameters given in Table 2.

For this example the focus is on the opaque wall, since windows are input separately in energy modeling software. From this basic outline of the building, we can look at two sets of details. One set where the thermal performance of the detail is not given much consideration (containing poor thermal performance details) and one where the details have been chosen to minimize the heat flow through them (containing efficient thermal performance details). These details and their transmittances, taken from ASHRAE RP-1365 and other similar reports, are given in Table 3.

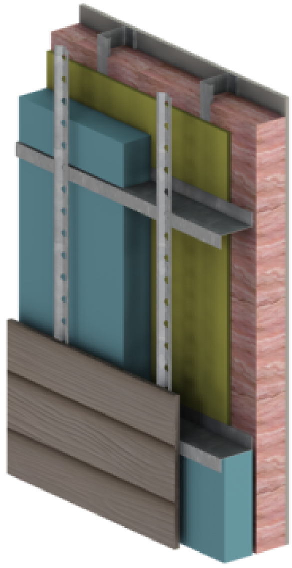

Figure 6 R-20 exterior and R-13 interior split insulated steel stud assembly with horizontal z-girts

Using these transmittances and the dimensional information given in Table 2, the total heat flow through the opaque wall for this elevation can be calculated using Equation 1, as can the individual heat flows through each of the details. These values are given in Table 4 along with their percentage contribution to the overall heat flow. The overall wall U- and R-values can also be calculated using Equation 2. These values are given in Table 5.

For this example, the actual heat flows values are not that important because the values will vary with building size. But what is important is the percent contribution that each component makes as part of the total heat flow. In this example, for the poor details, there is more heat flow through the slab (38%) than through the clear wall (25%). By analyzing the heat flow in this manner, it is much easier to see where improvements to the design would be most effective. For poor thermal performance details, increasing the amount of insulation may improve the clear field performance; however, it is likely more advantageous and cost effective to provide a thermal break at the slab, or insulate it, to achieve energy savings.

As illustrated in this example, accounting for details will show a large increase in calculated U-values, depending on what type of details are present. Compare

U-0.049 where thermal bridging is ignored, to U-0.064 where efficient details are considered, and to U-0.194 where poor details are considered. Not accounting for details can result in ignoring a significant amount of heat flow. For this example, the poor details have reduced the thermal resistance of the opaque building envelope by 75%, and this only takes into account four types of linear transmittances. There could be several additional types of transmittances that would also contribute to the heat flow. This dramatic decrease in thermal resistance is not limited to steel stud assemblies. Concrete mass walls may be very effective in the clear field, but those thermal benefits can be negated in the overall envelope performance with poor details.

While this example was for an entire elevation of a building, this approach can also be used for other divisions of a building, including single floors or even single walls of spaces, making it very easy to include in a zone by zone, whole building energy model.

EFFECTS OF THERMAL BRIDGES IN WHOLE BUILDING ENERGY SIMULATION

Whole building energy use and the building envelope

Determining the overall performance of opaque building envelope components including the effects of thermal bridging at details using the method of linear transmittance has been established above. To understand the impact on building energy use, the analysis must be extended to whole building energy modeling. The method of linear transmittance allows for easy integration into whole building energy models by inputting the modified thermal performance values on a surface by surface basis.

From the example given in the previous section, including the heat flow associated with the details can reduce the wall thermal resistance by 75%. When inputting the thermal resistance of the walls into an energy model, the question becomes *how much space heating energy is being missed when inaccurate thermal resistance values are modeled?*

Wall R-value sensitivity analysis

To see the effects of neglecting the heat flow through the details on building energy use, a sensitivity analysis was performed by plotting opaque building envelope R-values against space heating energy. The analysis was performed using EnergyPlus v 7.0.0 whole-building energy simulation software. The simulation used three building models from the U.S. Department of Energy's Commercial Reference Buildings (U.S. DOE 2011). The Commercial Reference Buildings are complete energy models of commercial buildings specifically created for using EnergyPlus simulation software to perform whole-building energy analysis. The models used are the large office, the medium office, and the midrise multi-unit residential building (MURB) with 15% and 60% glazing. A brief description of the building types is presented in Table 6. A detailed description of each building can be found in Deru et al. 2011. In this sensitivity analysis, the effective overall R-value of the walls was varied from R-5 to R-35. The building energy use was simulated in four cities: Minneapolis, Seattle, Houston, and Phoenix.

In most energy simulation software, the building envelope is modeled as series of layers where the thermophysical properties of each layer (conductivity, specific heat, density, etc.) is specified by the user. The procedure for converting the overall effective thermal transmittance—as determined using RP-1365—into appropriate inputs for energy simulation software is as follows. For each opaque assembly:

1. Determine the actual U-value using RP-1365 accounting for all the relevant linear and point transmittances in the assembly.
2. Input the assembly layer-by-layer into the energy simulation software and assign the nominal thermophysical properties to each layer.
3. Calculate the nominal U-value using the nominal thermophysical properties of each layer and ignore all thermal bridges (that is, calculate the inverse of the sum of the R-values of each layer).
4. In the energy simulation software increase the thermal conductivity of the insulation layer until the nominal U-value of the assembly is the same as the actual U-value that was calculated using RP-1365. Alternatively, in the energy simulation software, decrease the thickness of the thermal insulation layer until the nominal U-value is the same as the actual U-value.
5. In order to accurately simulate transient effects, such as thermal mass, it is important to accurately input the actual thermophysical properties of layers that have thermal mass, such as the correct thickness, density, and specific heat.

The annual energy use for heating the large office, medium office, midrise multi-unit residential building (MURB) with 15% glazing, and MURB with 60% glazing, are shown in Figures 7, 8, 9, and 10, respectively. The units for space heating energy are in MJ per m^2 of conditioned floor area.

Figures 7 to 10 show that space heating energy use is sensitive to changes in opaque building envelope performance at low thermal resistance values, but the effect decreases as the thermal resistance increases. Although the impact varies by climate and building type, the impact is significant in all cases at the lower ranges. As per Table 10, the example wall assembly had an assumed thermal resistance of R-20.4 if details are ignored, when in fact it could be as low as R-5.2 when details are considered, depending on the type of details used. In the 16 climate and building type scenarios described above, this difference of thermal performance (from R-5 to R-20) represents from 13 to 84% error in the calculated heating energy when thermal bridging is not considered. For example, in the Seattle MURB with 15% glazing, ignoring a reduction in R-value from R-20 to R-5 due to thermal bridging would result in 75 MJ/m^2·yr (164 – 89 / 89 = 84%) not being accounted for. Similarly, in Minneapolis, 115 MJ/m^2·yr would not be accounted for. When the glazing area in the MURB is increased to 60%, more heating energy is needed to make up for the overall lower envelope R-value regardless of opaque wall R-value, so the relative percent difference in heating energy not accounted for is less. But the absolute amount of heating energy that is not accounted for is still significant in the colder climates: 55 MJ/m^2·yr in Minneapolis and 36 MJ/m^2·yr in Seattle. In the two office buildings, not accounting for thermal bridging also has a significant impact on heating energy: 13% to 27% in the large office and 24% to 40% in the medium office. These results illustrate the importance of properly accounting for the heat flow through the details.

The annual energy use for cooling in the large office, medium office, midrise multi-unit residential building (MURB) with 15% glazing, and MURB with 60% glazing, are shown in Figures 11, 12, 13, and 14, respectively. The units for space cooling energy are in MJ per m^2 of conditioned floor area. This cooling energy includes the energy for fans, pumps, and heat rejection equipment.

Figures 11 to 14 show that space cooling energy use is sensitive to changes in opaque building envelope performance at low thermal resistance values, but the effect decreases as the thermal resistance increases. Although the effect of not accounting for thermal bridging on cooling energy is not as significant as it is for heating, it can represent a significant portion of the cooling load in some buildings in some climates. For example, in the Phoenix MURB with 15% glazing using the same reduction as above (R-20 to R-5), 23 MJ/m^2·yr (22%) of the cooling energy would not be accounted for.

In order to put space heating energy use into context for the different building types modeled, a breakdown of building energy by end use is presented in Figure 15 for Minneapolis and an overall effective thermal resistance of R-15 for the opaque wall.

The data shows that space heating energy use is a significant portion of the overall building energy use, regardless of building type, ranging from a low of about 25% in the large office to 50% in the MURB with 60% glazing.

Further discussion

Adding more insulation to a wall assembly has multiple levels of diminishing returns. First, increasing the insulation in clear field assemblies becomes less and less effective due to heat flow bypassing the insulation through the assembly thermal bridges, such as studs and cladding attachments. This clear wall effect was also studied in ASHRAE RP-1365 and can be seen clearly in ASHRAE 90.1, Appendix A (ASHRAE, 2007), which contains tables for U-values for varying insulation levels for several assemblies with continuous insulation. Diminishing returns manifest again at the detail level when poor thermal performance details cause heat flow to completely bypass the clear wall. Adding insulation will only slightly improve the clear wall; however, the heat flow through the details will not be improved. This results in a minimal overall improvement on the opaque building envelope thermal performance. From the point of view of sustainability, it does not make sense to use more materials like insulation, when it is not performing its intended function. Finally, as shown in Figures 7 to 10, as the R-value increases, the impact on the space heating energy decreases and eventually levels out. After exceeding a certain level of opaque building envelope thermal performance, energy savings are no longer realized. Thus, increasing the amount of insulation may have very little influence on the overall energy use in a building if other major heat flow areas are not addressed.

CONCLUSIONS

This paper presented concepts introduced in ASHRAE RP-1365 to efficiently analyze the heat flow through various building details and their influence on whole building energy. Accounting for heat flow through details is not typical in North America, nor is it explicitly required in current energy codes and standards. However, the results presented in this paper highlight the significance of thermal bridges that are often overlooked, suggesting that they should no longer be ignored. The method of linear transmittance provides a simple yet effective way to determine the overall thermal transmittance through the opaque building envelope. This approach is useful for energy modelers, not only in calculating thermal values for input into whole building energy models, but also in understanding what overall thermal resistance values can be realistically achieved in practice.

The results show that when poor details exist, solely adding increasing levels of insulation to the clear wall does not result in any considerable decrease in overall building energy use. When examining the thermal performance of the clear wall on its own, increasing the amount of insulation does not significantly increase the overall wall thermal resistance when large amounts of heat bypass the insulation through structural members. The same effect can be seen when looking at the entire opaque wall area, including details. If the clear wall has a high thermal performance, but heat can flow easily through poor details, then the overall wall thermal resistance will always remain low, regardless of how much insulation is added.

On the other hand, if the details and clear wall are both thermally efficient, but the glazing percentage and/or window U-values are very high, then the thermal resistance of the opaque wall has a much smaller influence on space heating. A thermally efficient building envelope must address all heat flow in order to have an appreciable impact on overall energy use. Weak points in the building envelope can occur in the clear field (framing, structural supports), in the details (slabs, parapets), or through the glazing (windows, patio doors). When determining the most effective solutions for minimizing building energy use, the key is in addressing those constructions with the poorest thermal performance. The analysis described here provides the tools to effectively evaluate the heat flow through the entire envelope to help identify and address any areas of poor performance.

In previous work, it has been shown that building envelope performance has a minor impact on overall building energy use when only the clear field assemblies have been considered (Lucuik et al. 2008). However, the impact is more pronounced at lower thermal resistance values, which is representative of many wall assemblies when standard details are considered. Thermal bridging at structural and architectural details cannot be avoided, but there can be a wide range in overall thermal transmittance depending on the thermal quality of the details.

There is an opportunity to realize greater energy savings in buildings if more attention is paid to the building envelope details during design. This can be achieved by conducting a sensitivity analysis of the building envelope's performance compared to overall energy use, as presented in this paper. Also, by breaking down the building envelope into components for clear wall and details, and determining overall wall thermal resistance using the method of linear transmittance, it becomes possible to easily target where improvements are most effective. An increased awareness of the impact of the overall thermal performance of the building envelope, by utilizing these methods, can be incorporated in practice by the entire design team (energy modeler, architect, contractor, HVAC designer, etc.) to make informed decisions that consider cost, energy efficiency, and material use.

Table 1 Linear Transmittance Ranges

Transmittance Range	Linear Transmittance Value Btu/hr·ft·°F (W/m·K)			
	Slabs	**Parapets**	**Corners**	**Window Transition**
Low: efficient (Fully insulated, thermally broken systems)	< 0.15 (< 0.25)	< 0.20 (0.35)	< 0.03 (0.05)	< 0.05 (< 0.10)
Medium: average (Partially insulated systems, small conductive bypasses)	0.15 - 0.30 (0.25 - 0.50)	0.20 - 0.40 (0.35 - 0.70)	0.03 - 0.15 (0.05 - 0.25)	0.05 - 0.10 (0.10 - 0.20)
High: poor (Un-insulated systems, large conductive bypasses)	> 0.30 (> 0.50)	> 0.40 (> 0.70)	> 0.15 (> 0.25)	> 0.10 (> 0.20)

Table 2 Example building

Building Parameter	**Building Parameter Value**
Wall width	30 ft (9.1 m)
Wall height	100 ft (30.5 m)
Number of floors	10
Glazing %	40%
Window perimeter length	28 ft (8.5 m)
Number of windows	25
Opaque wall area	1800 ft^2 (167.2 m^2)
Wall assembly: R-20 exterior insulated steel stud wall with horizontal Z-girts and R-13 batt in stud cavity	U-0.049 Btu/hr·ft^2·°F (U_{SI}-0.28 W/m^2·K)

Table 3 Example linear transmittances

Detail	Linear Transmittance Btu/hr·ft·°F (W/m·K)	
	Efficient Details	**Poor Details**
Slab edge	Insulated slab face	Un-insulated balcony slab
	0.02 (0.04)	0.45 (0.78)
Parapet	Fully insulated concrete	Un-insulated concrete
	0.15 (0.26)	0.45 (0.78)
Corner	Mitered and sealed corner	Butted corner with flashing
	0.03 (0.05)	0.09 (0.16)
Window transition	Isolated flashing	Through metal flashing transition
	0.02 (0.04)	0.15 (0.26)

Table 4 Heat flow values for example building

Transmittances	Heat Flow Btu/hr·°F (W/K)			
	Efficient Details	**%**	**Poor Details**	**%**
Clear field	88	77%	88	25%
Slab edge	6	5%	134	38%
Parapet	5	4%	14	4%
Corner	3	2%	9	3%
Window transition	14	12%	105	30%
Total	**115**	**100%**	**349**	**100%**

Table 5 Wall thermal performance for example building

Transmittance Range	Opaque Wall R-Value (RSI)	Opaque Wall U-Value (USI)
Clear field only (not including details)	R-20.4 (RSI-3.59)	U-0.049 (USI-0.28)
Including efficient thermal performance details	R-15.6 (RSI-2.75)	U-0.064 (USI-0.36)
Including poor thermal performance details	R-5.2 (RSI-0.91)	U-0.194 (USI-1.10)

Table 6 Example building characteristics

Building Size	Building Type	Glazing %	HVAC System
Large office, 12 floors plus basement	Office	40	Two water-cooled chillers, boiler, VAV reheat
Medium office, 3 floors	Office	33	Packaged multi-zone VAV, gas furnace, electric reheat
Midrise multiunit residential, 3 floors	MURB	15	Split system in each residence (DX cooling and gas furnace)
Midrise multiunit residential, 3 floors	MURB	60	Split system in each residence (DX cooling and gas furnace)

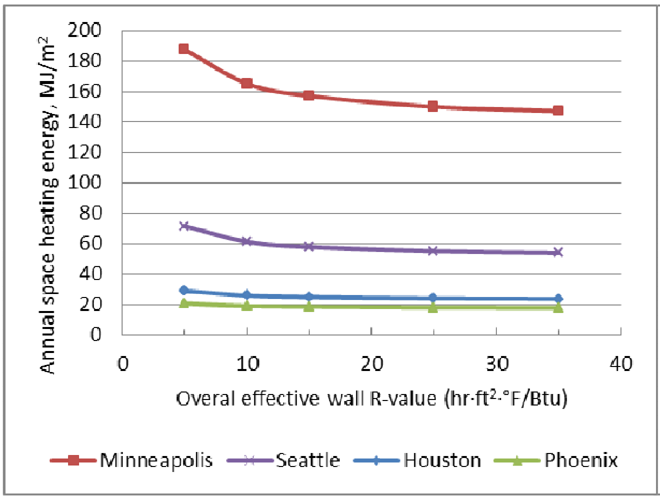

Figure 7 Effects of opaque wall thermal resistance on space heating for a large office

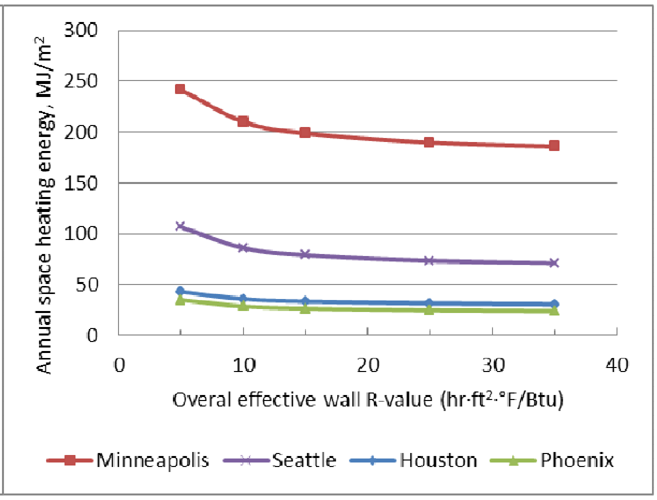

Figure 8 Effects of opaque wall thermal resistance on space heating for medium office

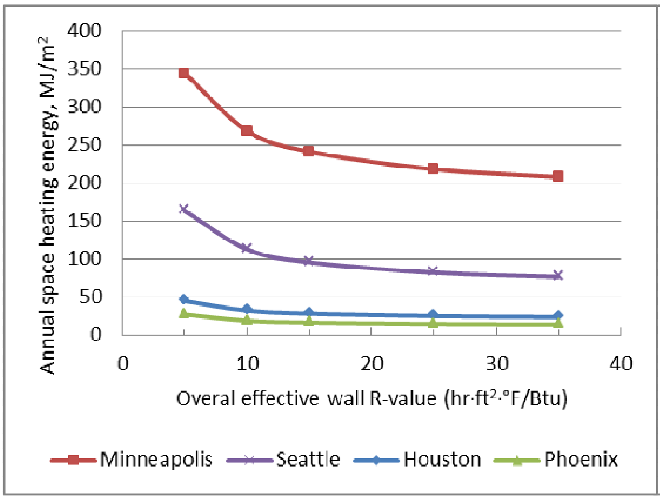

Figure 9 Effects of opaque wall thermal resistance on space heating for midrise MURB with 15% glazing

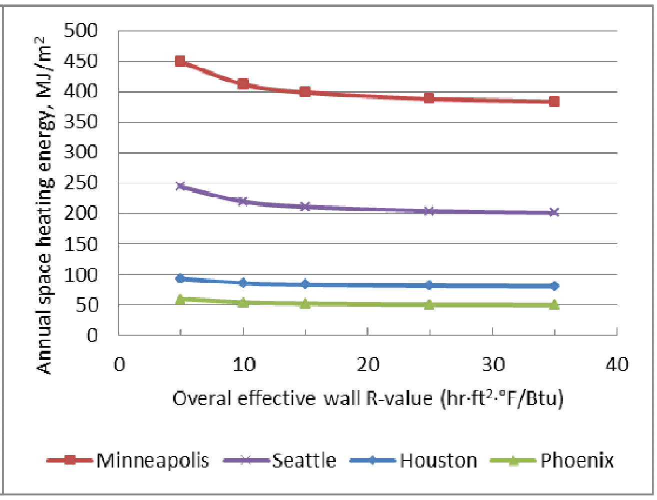

Figure 10 Effects of opaque wall thermal resistance on space heating for a midrise MURB with 60% glazing

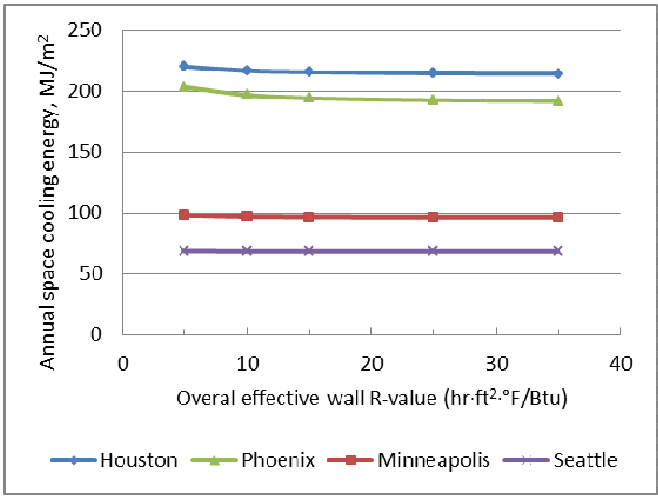

Figure 11 Effects of opaque wall thermal resistance on space cooling for a large office

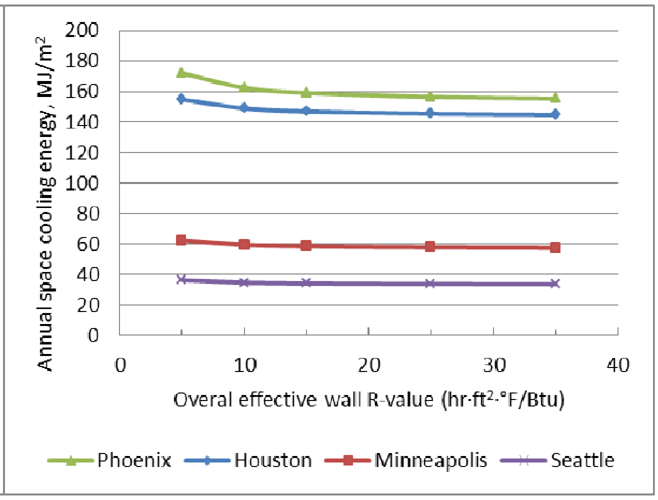

Figure 12 Effects of opaque wall thermal resistance on space cooling for medium office

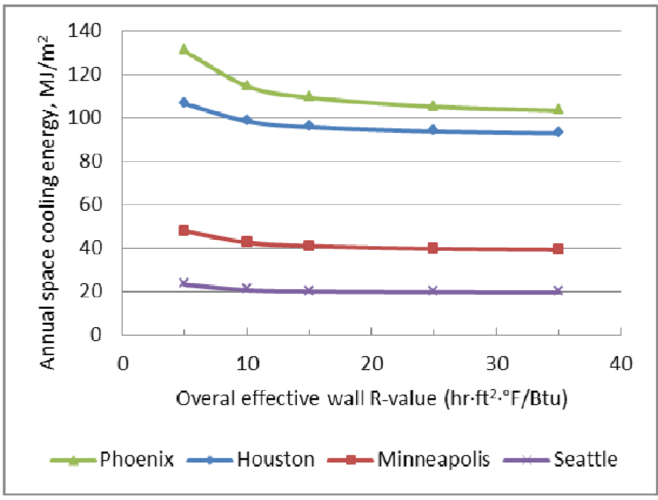

Figure 13 Effects of opaque wall thermal resistance on space cooling for midrise MURB with 15% glazing

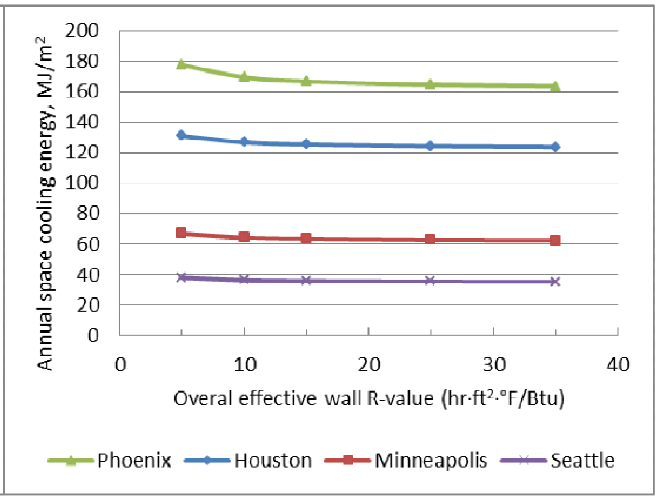

Figure 14 Effects of opaque wall thermal resistance on space cooling for a midrise MURB with 60% glazing

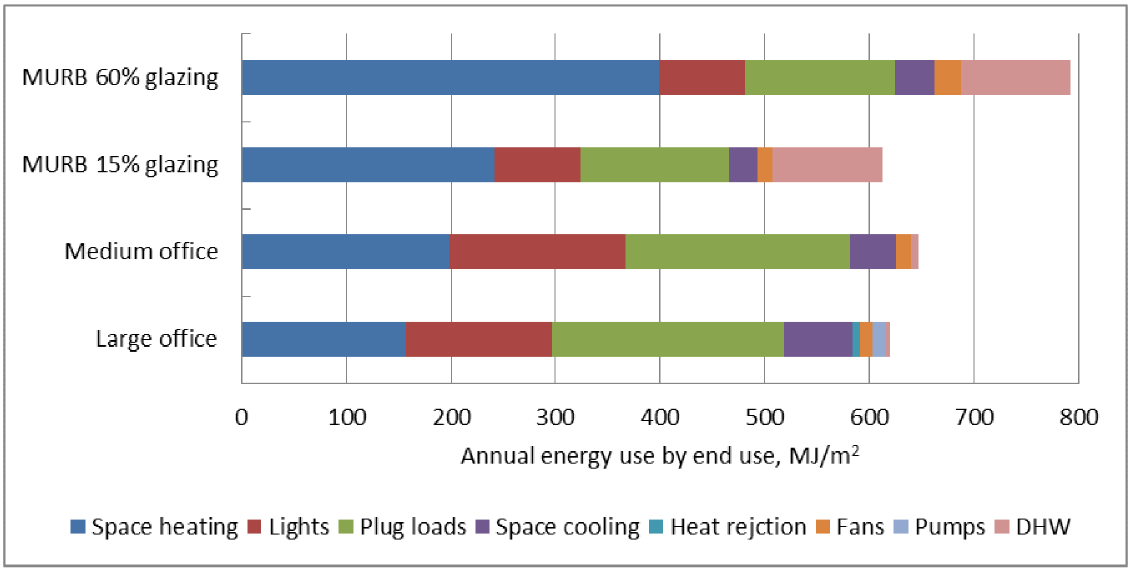

Figure 15 Annual building energy by end use for various building types in Minneapolis with an effective wall thermal resistance of R-15

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