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 insulating layers can greatly reduce the thermal performance of building assemblies and have a significant impact on whole-building energy performance. As such, determining the effects of thermal bridging is often of importance to energy modelers, building engineers and architects in accurately designing and assessing the performance of buildings. This, however, can be very difficult to accomplish using common approaches, such as the area-weighted average of U-values, especially when dealing with three dimensional heat flow paths.

In ASHRAE Research Project 1365 (1365-RP), a methodology was developed, using a calibrated 3D model, that enables designers to consider all thermal bridging 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 1365-RP and its potential impact on energy simulation. These impacts on whole building energy performance will be examined for various building and construction types, and climate zones.

1 Introduction

Building owners and operators are 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 within each specific building system. With regards to the building envelope, building regulators have responded by steadily increasing the thermal performance requirements in building codes and standards over the last 20 years. Designers have typically been addressing these building envelope requirements by adding more insulation, with little attention being paid to thermal bridging.

Standard practice in North America for accounting for thermal bridging within the building envelope is to consider thermal bridging within an assembly, for example steel framing, but to ignore thermal bridging at architectural and structural details at intersections of walls, windows, floors, and roofs. Whole building energy modeling procedures for the purposes of performance based compliance in many North American energy standards are either largely silent on thermal bridges relating to details (i.e. slab edges, shelf angles, flashings), allow these thermal bridges to be ignored through partial or full exemptions, or reduce their significance through oversimplification. The reasons for these omissions appear to be based on:

1. The details comprise of a small area compared to the total envelope area; therefore these details may not have a significant impact on the overall building envelope performance and whole building energy use.
2. The significant effort required to quantify all thermal bridging, which often have complex three dimensional heat flow paths.
3. The lack of comprehensive thermal transmittance data for standard details.

Incorporating the 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. Irrespective of the small areas of highly conductive materials that bypass the thermal insulation, the effect on overall energy consumption is measureable and simple changes to assembly design may be more effective at reducing energy than adding more insulation. In addition, accounting for these details is less onerous; straightforward procedures to quantify the impact of common details have been developed and thermal transmittance data for standard details is readily available. Moreover, 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 “Thermal Performance of Building Envelope Details for Mid- and High-Rise Construction” (1365-RP) to show how easily the impact of all thermal bridging can be integrated into the overall thermal performance of the building envelope and 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 cold and mild climates.

2 Current Practices in Accounting for Thermal Bridges

The common practice in North America to calculate the thermal performance of assemblies and details is to use an area weighted-average, but unfortunately this method has many drawbacks. 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.

While areas may be easily determined for large, flat surfaces like windows or typical wall assemblies, the area of influence of details like slab edges, parapets and window transitions are much more difficult to define. Lateral heat flows, like those shown in Figure 2.1, complicate the process. The effective lengths, the length where a thermal bridge has influence on the wall assembly, can be drastically different depending on the starting point of the analysis. This can lead to lengthy calculations or ultimately arbitrary definitions for the areas, 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 1145-RP requires at least 5 equations to calculate the overall transmittance for a simple building using the area-weighted method.

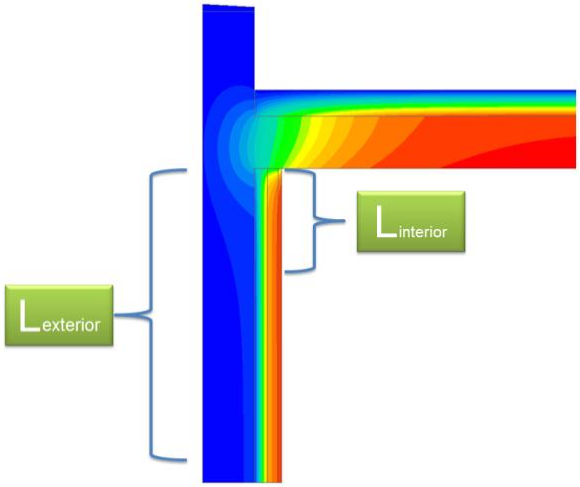

Figure 2.1: Effective lengths for area-weighted calculations for parapet from exterior and interior

The other major drawback to this approach is that it is harder to quantify the individual contribution of a single thermal bridge. The effects are averaged over the entire area, diluting the impact of the thermal bridge with the clear field heat flow. For example, the averaged results of the same slab detail will have less of an effect on a 12 ft ceiling height than a 9ft 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 weighted method to calculate thermal values consistently and to apply them generically for practical use beyond a single project.

3 ASHRAE 1365-RP and the Method of Linear Transmittance

ASHRAE Research Project 1365 – Thermal Performance of Building Envelope Details for Mid- and High-Rise Buildings (1365-RP)

ASHRAE 1365-RP was initiated to address the uncertainty related to the thermal performance of the building envelope, which can lead to inefficient design of HVAC systems, building operation inefficiencies, inadequate condensation resistance at intersections of components, and compromised occupant comfort. ASHRAE 1365-RP's objective 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 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'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.

The Method of Linear Transmittance

A key finding of 1365-RP 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 1365-RP employed the method of linear transmittance to characterize thermal bridging in details to overcome the drawbacks in the area weighted method.

Instead of trying to find areas of influence, this approach takes the absolute heat flow increase caused by a thermal bridge and prescribes it to simple mathematical constructs of lines and points. An example of the simplified process for a slab is shown in Figure 3.1

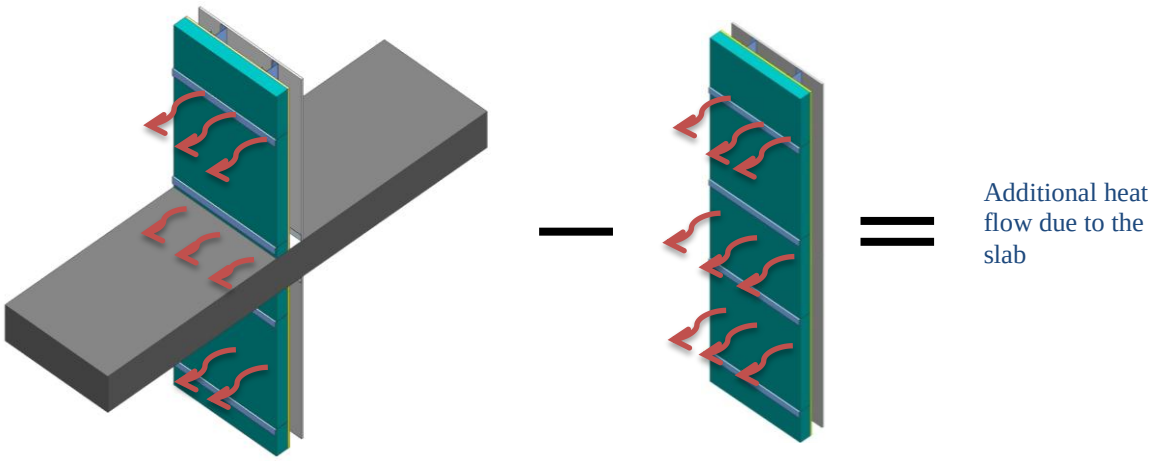

Figure 3.1. Determining linear transmittance for a slab

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 allows thermal bridging in details to be treated separately from the wall or roof assemblies. This simplifies calculations as areas for 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 divided into three categories, clear field transmittance, linear transmittance and point transmittances, shown in Figures 3.2,3 and 4 respectively.

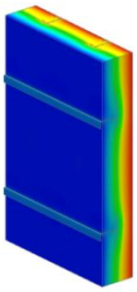

Figure 3.2: Example clear field assembly

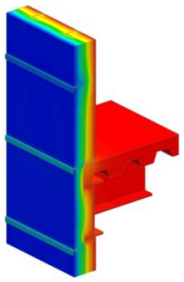

Figure 3.3: Example linear transmittance detail

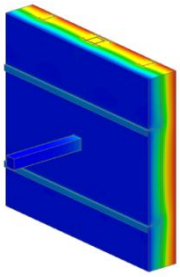

Figure 3.4: Example point transmittance detail

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 structural framing, brick ties and cladding supports. This is treated the same as in standard practice, defined as a U-value, U_o (heat flow per area). For a specific area of opaque wall, this 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. This includes 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 the linear 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:

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

Where:

Q =	Overall heat flow from the wall or roof including all thermal bridges (Btu/hr·^{o}F or W/K)
$Q_{thermalbridge}$ =	the additional heat flow caused by major thermal bridges (Btu/hr· ^{o}F or W/K)
Q_o =	Heat flow from the clear field assembly (Btu/hr· ^{o}F or W/K)
Ψ =	Heat flow from linear thermal bridge (Btu/hr·ft ^{o}F or W/mK)
L =	Characteristic length of linear thermal bridge (ft or m)
χ =	Heat flow from point thermal bridge (Btu/hr· ^{o}F or W/K)

The overall heat flow through the wall or roof, Q, is the summation of all of the thermal bridges with the clear field heat flow. There may be several different types of linear and point transmittances but they are all included in the final value. For this calculation, L is the characteristic length of the linear thermal bridge. For a slab edge, this would be the length the details occurs 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. This can assist designers in making better decisions in improving the building envelope.

Equation 1 gives 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·^{o}F or W/m^{2}K)

U_o = clear field thermal transmittance (Btu/hr·ft^2·^{o}F or W/m^{2}K)

A_{total} = the total opaque wall area (ft^2 or m^2)

While this method could be applied to glazing, the analyses of these constructions are already well established in the North American building industry. Since glazing 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 glazing.

ASHRAE 1365-RP 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 1365-RP 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, pre-cast concrete walls

and brick veneer 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 to provide designers a means for a quick approximation of surface temperatures.

The linear transmittances can 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, a partially insulated slab edge with a metal flashing would be in the medium range, and a fully insulated slab face would be in the low range. Examples for these linear transmittance ranges are shown below in Table 3.1.

Table 3.1. Linear Transmittance Ranges

Transmittance Range	**Linear Transmittance Value Btu/hr·ft ^{o}F (W/mK)**			
	Slabs	Parapets	Corners	Window Transition
Efficient (Fully insulated, thermally broken systems)	< 0.15 (< 0.25)	<0.20 (0.35)	<0.03 (0.05)	<0.05 (<0.10)
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)
Poor (Un-insulated systems, large conductive bypasses)	> 0.30 (>0.50)	>0.40 (>0.70)	>0.15 (>0.25)	>0.10 (>0.20)

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 included in a catalogue, without having to be explicitly modeled. With some judgement, a specific design can be compared to a similar detail in the catalogue and estimated whether it is likely better or worse in thermal performance.

The amount of additional heat flow will depend on the frequency of the details. 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, simply because the slab occurs more often.

Using Linear and Point Transmittances in Practice

The following example has been prepared to illustrate the practical use of the linear and point transmittance approach. Take a single elevation of building with an R-20 exterior and R-12 interior split insulated steel stud assembly, as shown in Figure 3.5, with the building parameters given in Table 3.2.

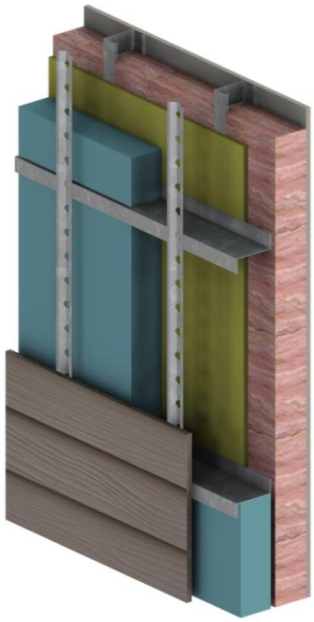

Figure 3.5: R-20 exterior and R-12 interior split insulated steel stud assembly with horizontal z-girts

Table 3.2: Example building

Building Parameter	**Building Parameter Value**
Wall Width	30ft (9.1m)
Wall Height	100ft (30.5m)
# of floors	10
Glazing %	40%
Window Perimeter Length	28ft (8.5m)
# of Windows	25
Opaque Wall Area	1800 sqft (167.2m^2)
Wall Assembly - R-20 Exterior insulated steel stud wall with horizontal Z-girts and R-12 Batt	U-0.049 Btu/hrft^{2o}F (USI-0.28 W/m^2K)

For this example the focus is on the opaque wall, since windows are inputted separately into energy models. 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 1365-RP and other similar reports, are given in Table 3.3.

Table 3.3: Example linear transmittances

Detail	Linear Transmittance Btu/hr·ft ^{o}F (W/mK)	
	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)

Using these transmittances and the dimensional information given in Table 3.2, 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 3.4 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 3.5

Table 3.4: Heat flow values for example building

Transmittances	Heat Flow Btu/hr· ^{o}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 3.5: 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)

For this example, the actual values of the heat flows are not as important, as they vary depending on the building size. 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 than through the clear wall. 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, accounting for details can potentially show a large difference in calculated U-values, depending on what type of details are present. 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. Potentially there can be several additional types of transmittances that could 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 are 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.

4 Effects of Thermal Bridges in Whole Building Simulation

Whole Building Energy 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 this impact on building energy use, the analysis must be extended to whole building energy modelling. 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 modelled?*

Wall R-value Sensitivity Analysis

To see the effects of neglecting the heat flow through the details on building energy, a sensitivity analysis was performed by plotting opaque building envelope R-values against space heating energy. The analysis was performed using eQUEST v3.64, an hourly, whole building simulation tool. Throughout the analysis, the model input thermal resistance was varied from R-5 to R-35 for four different Canadian climate zones and four building types. The example buildings are summarized below in Table 4.1.

Table 4.1. Example building characteristics

Building Size	Building Type	Glazing %	Window U-value	HVAC System	Internal Loads
Low-Rise 5 Floors	Office	40	U-0.45 (USI-2.6)	VAV	19.5 W/m^2
Mid-Rise 15 Floors	MURB	40	U-0.45 (USI-2.6)	FPFC	12.9 W/m^2
High-Rise 40 Floors	MURB	40	U-0.45 (USI-2.6)	FPFC	12.9 W/m^2
High-Rise 40 Floors	MURB	70	U-0.45 (USI-2.6)	FPFC	12.9 W/m^2

The results from the sensitivity analysis for the low-rise office, mid-rise MURB, high-rise MURB with 40% glazing, and high-rise MURB with 70% glazing are shown in Figures 4.1, 4.2, 4.3 and 4.4, respectively. The units for space heating energy are in GJ per m^2 of conditioned floor area.

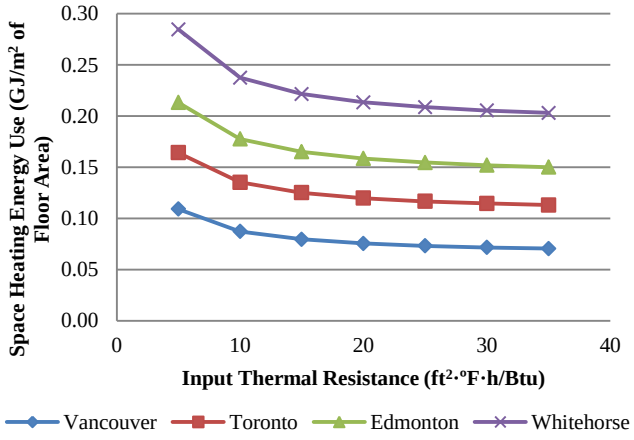

Figure 4.1: Effects of variations of opaque wall thermal resistance on space heating for a low-rise office

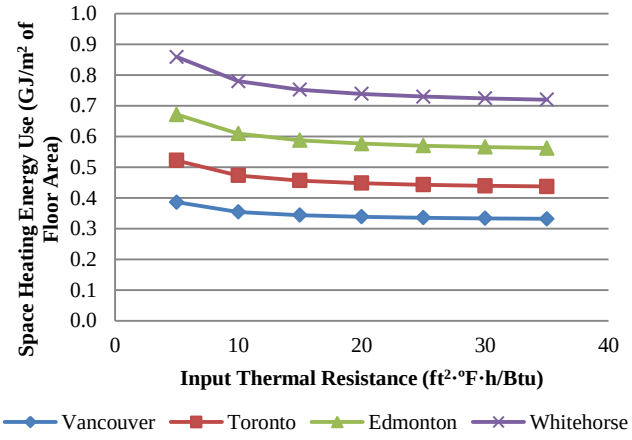

Figure 4.2: Effects of variations of opaque wall thermal resistance on space heating for a mid-rise MURB

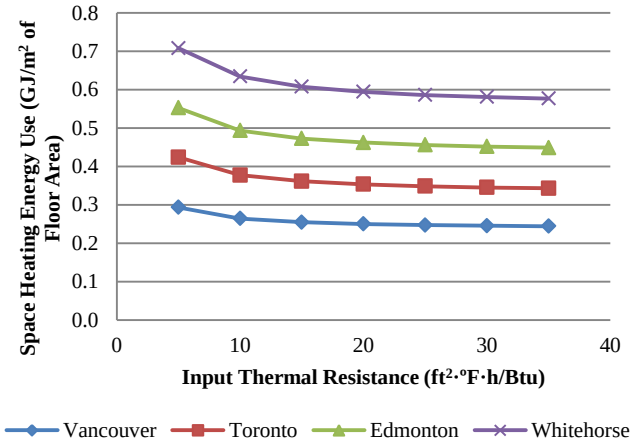

Figure 4.3: Effects of variations of opaque wall thermal resistance on space heating for a high-rise MURB

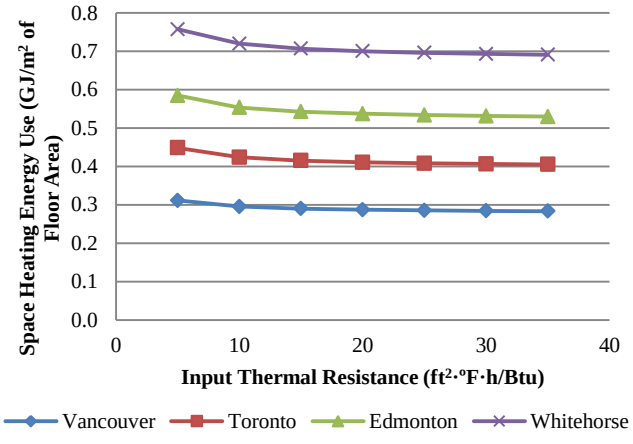

Figure 4.4: Effects of variations of opaque wall thermal resistance on space heating for a high-rise MURB with 70% Glazing

Figures 4.1 to 4.4 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 3.5, the example wall assembly has an assumed thermal resistance of R-20.4 when 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 plotted above, this range of thermal performance can represent changes in space heating energy of anywhere from 8% to 45%. This illustrates the significance of properly accounting for the heat flow through the details.

The impact of thermal resistance on space heating energy use becomes more dramatic as the overall building energy efficiency improves. Figure 4.5 shows a sensitivity analysis of thermal resistance values versus space heating energy for a high-efficiency, mid-rise MURB, where air infiltration has been minimized and the efficiency of other building systems, such as glazing, heating, ventilation, domestic hot water, and lighting have increased. The graph shows up to a 58% difference in space heating energy use for the example assembly if the heat flow through details is ignored.

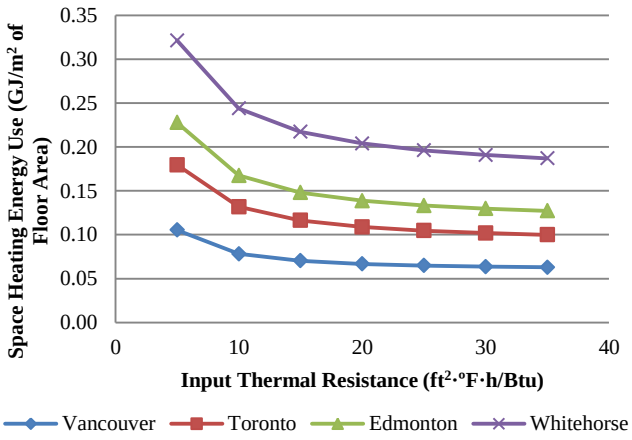

Figure 4.5: Effects of variations of opaque wall thermal resistance on space heating for a mid-rise high efficiency MURB

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 4.6 for the Toronto climate and an input thermal resistance of R-15.

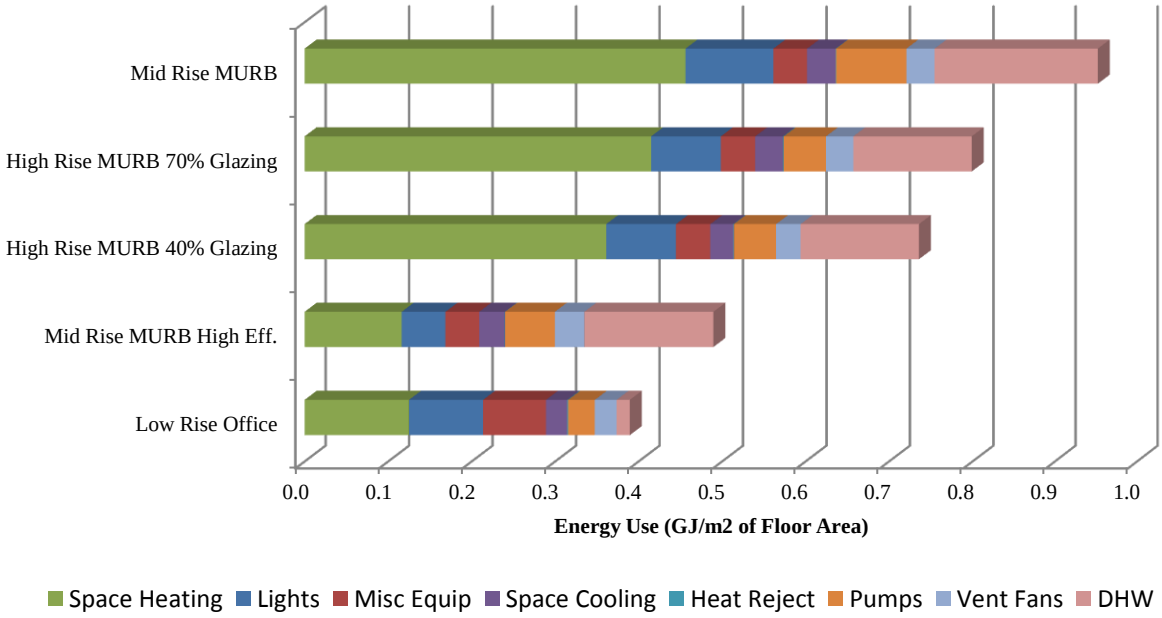

Figure 4.6: Total building energy by end use for various building types with Toronto climate and a wall thermal resistance of R-15

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 high efficiency, mid-rise MURB to a high of approximately 50% in the high-rise MURB with 70% glazing area.

Further Discussion

Adding increasing levels of 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 1365-RP 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. This occurs 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 performance as stated above, 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. Finally, in Figures 4.1-4.5, 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. This concept of compounding diminishing returns is exemplified in Figure 4.7, which shows how increasing amounts of exterior insulation for the example assembly in Figure 3.5 affects the energy use related to the building envelope for a mid-rise MURB located in Edmonton (based on the curves in Figure 4.2).

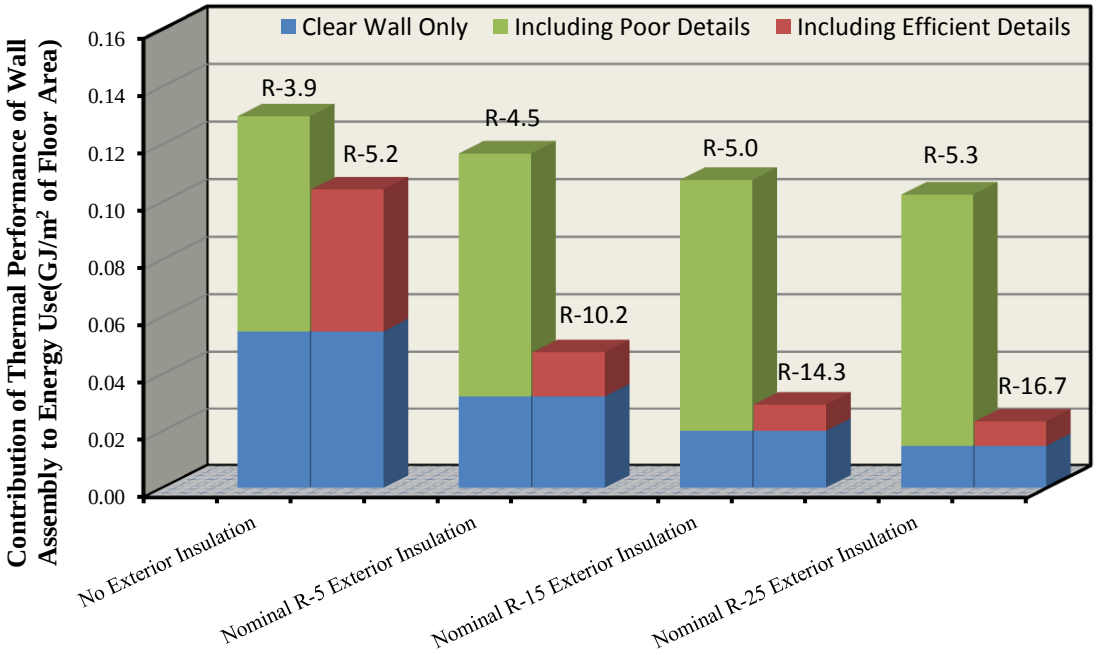

Figure 4.7: Additional building energy use based on thermal performance of the building wall assembly for varying amounts of nominal exterior insulation for a mid-rise MURB in Edmonton (overall assembly thermal resistance in $ft^2 \cdot °F \cdot h/Btu$ also given)

With no exterior insulation and not accounting for the heat flow through the details, the clear wall has a thermal resistance of R-9.2. Accounting for the heat flow through poor performing details brings it down to R-3.9 and more than doubles the energy use related to the opaque building envelope. When exterior insulation is added, but poor performing details that bypass the insulation have not been addressed, there is only a small drop in energy use. When going from no exterior insulation to R-25 (approximately 5" of XPS), overall the system has only effectively increased from a thermal resistance of R-3.9 to R-5.3. While this is on the steep end of the curve in Figure 4.2, the reduction in energy use is still minimal considering the costs associated with installing R-25 of exterior insulation across an entire mid-rise building.

Now compare the energy use for the poor performing details to the efficient details. The drop in energy use between the poor performing and efficient details with no exterior insulation is almost as effective as adding R-25 exterior insulation without improving the details. The most dramatic improvement in energy use is achieved by improving the performance of both the clear wall and details. By using efficient details, there is a much greater justification for increasing exterior insulation. However, as per Figures 4.1 to 4.5, after thermal resistance values of between R-10 to R-15, the rate in energy use reduction drops.

5 Conclusions

This paper presented concepts introduced in ASHRAE 1365-RP to efficiently analyze the heat flow through various building details and their influence on whole building energy. The practice of accounting for heat flow through many 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 modellers, 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 clearly indicate that when poor details exist, solely adding increasing levels of insulation to the clear wall does not result in any considerable improvements 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 weakest 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 weaknesses.

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 incorporated. 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; to make informed decisions that consider cost, energy efficiency, and material use.

6 References

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