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A NUMERICAL RELATIONSHIP FOR EFFECTIVE R-VALUE ESTIMATION OF SHELF ANGLE SYSTEMS FOR MASONRY VENEER

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ABSTRACT

New energy codes for buildings in Canada require energy losses associated with thermal bridging to be accounted for by designers. In masonry systems, most of the energy losses from thermal bridging are due to structural penetrations at floor levels located at shelf angles. This is because most of the shelf angle systems currently used in practice are made of steel, which is a highly conductive material. New technologies, such as plastic polymer, have been proposed to reduce the bridging losses, but there are few studies on the effect of the various technologies. 3D thermal modeling provides accurate predictions of thermal performance when addressing masonry thermal bridging. This study used 3D thermal modeling to investigate the influence of various parameters (e.g. stand-off shelf angle connector geometry, thermal properties, spacing of stand-off connectors, insulation thickness). The results of the 3D modeling were used to help determine a numerical relationship that can be applied to calculating thermal bridging effects.

KEYWORDS: *heat transfer, masonry wall systems, R-value estimation, shelf angles, thermal bridging, thermal modeling*

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INTRODUCTION

Traditional steel shelf angle systems are often used on multi-storey residential, commercial and institutional buildings to support full-bed masonry veneers. These shelf angles must now comply with the NECB (National Energy Code of Canada for Buildings). Since transitioning from NECB 2011 to NECB 2017, more stringent requirements for calculating the overall thermal transmittance of the building assembly have been implemented. NECB 2011 excluded major structural elements and other elements that completely penetrate the building envelope as long as the sum of the cross-sectional areas were less than 2% of the above-ground building envelope area [1]. This 2% allowance was removed in NECB 2017 to improve the thermal performance of buildings in Canada. NECB 2017 requires that all structural penetrations, including those with areas less than 2%, must now be accounted for [2] in an analysis of the thermal transmittance of a building's envelope. This is a significant change for masonry wall systems because it requires that both masonry ties and masonry shelf angles that were typically exempt from thermal bridging calculations in NECB 2011, must be now accounted for in the calculation of overall thermal transmittance.

NECB 2017 offers three paths of compliance: prescriptive, trade-off, and performance. In regards to thermal transmittance, the prescriptive path presents minimum RSI values with respect to the building envelope, that must be met. The trade-off path offers some flexibility in design for the above-ground assemblies, given that the calculated overall transmittance of the proposed building is not more than the overall transmittance of the reference building. The performance path offers the most flexibility in design, provided that the simulated energy consumption of the proposed building is equal to or less than the reference building, whose performance is based upon the prescriptive requirements of the code [2].

The performance path is typically favored among designers as it offers the most flexibility. In order to account for the diverse and sometimes proprietary technologies available, as well as the complexity of large wall assemblies, 3D computer simulations are required. Simple hand calculations or 2D models are typically insufficient and less accurate for this level of complexity. The downside of 3D computer simulations is that it can be time consuming and the software required can be costly. In efforts to address this and to make the comprehensive thermal bridging modelling more accessible, Morrison Hershfield Limited and BC Hydro released a "Building Envelope Thermal Bridging Guide". This guide is referenced in NECB 2017 as an acceptable resource to use in thermal bridging calculations. The guide is essentially a database that provides building envelope details that account for the impact of thermal bridging of various assemblies, which include both generic and proprietary systems [3]. The guide is an exhaustive and comprehensive list of assemblies that addresses many of the current needs for thermal bridging calculations without the use of 3D computer simulations.

Expanding on the current path of providing thermal bridging values without the use of complicated 3D computer simulations is the most practical method, as it provides more accessibility for those who need it. By making it easier and less complicated, accounting for thermal bridging will feel less like a chore for designers and can help promote a more positive attitude towards more energy efficient building envelope designs. Currently, the Building Envelope Thermal Bridging Guide provides a comprehensive list for their thermal bridging calculations, which utilizes plug and play values, but a complete list for all scenarios is naturally unattainable. This paper presents 3D thermal computer simulations with a focus on varying insulation thickness, stand-off shelf angle connector configuration (proprietary bracket and traditional knife plates), stand-off material (Hot-Dipped Galvanized (HDG) Steel and Glass Fibre Reinforced Polymer (GFRP)) and stand-off spacing (1.22m and 0.610m), to establish a numerical relationship that accounts for these various parameters and captures a range of scenarios, rather than simply a single value or a single scenario.

METHODOLOGY

A total of 26 3D models were simulated under steady-state thermal analysis conditions using the commercially available 3D finite element analysis ANSYS software. A concrete block back-up wall was used in all 26 cases. The equations, assembly details, and model assumptions are described below.

Equations

The numerical outputs from the ANSYS thermal models are given as heat flux density, q (W/m^2), measured across the entire exterior face of the exterior film. This value is then converted into a series of different variables using Equations (1) to (4) to arrive at a final linear thermal transmittance value, ψ (W/mK), as described in the Building Envelope Thermal Bridging Guide [4]. The conversion to a linear transmittance is necessary so that the data can be used in collaboration with methods outlined in the Thermal Bridging Guide, thus maximizing the use of these findings for a larger group of practitioners.

To convert q (W/m^2) to thermal transmittance per unit area, u (W/m^{2}K):

$$u = \frac{q}{\Delta T} \tag{1}$$

where

ΔT is the temperature difference applied to the model.

And to convert u (W/m^{2}K) to thermal transmittance of a given area, U (W/K):

$$U = u \cdot Area_{wall} \tag{2}$$

where

$Area_{wall}$ is the area of the exterior wall, taken as the product of the overall height and overall length of the wall as defined in Table 1.

To find the ψ (W/mK) value of the full wall assemblies, the thermal transmittance of the clear wall assemblies must be incorporated into the calculation [3, 5]. A clear wall assembly model removes major structural penetrations like a shelf angle but includes elements like masonry ties along with the other basic components like insulation, back-up/ framing, exterior materials. With respect to the models in this study, the main difference between the clear wall assemblies and full wall assemblies is that the concrete slab, shelf angle, and shelf-angle offset connectors are removed in the clear wall assembly.

$$\psi_{full\ wall} = \frac{U_{full\ wall} - U_{full\ wall\_clear\ wall}}{L_{wall}} \quad (3)$$

where

$U_{full\ wall\_clear\ wall}$ is the thermal transmittance of the full wall assemblies, calculated using Equation (2), above;

$U_{clear\ wall}$ is the thermal transmittance of the clear wall for the full wall assembly, also calculated using Equation (2), above;

and L_{wall} is the overall length of the wall as defined in Table 1.

To establish a numerical relationship between the various scenarios, multiplicative factors, or multipliers, were given to each model solution. The multipliers were determined using Equation (4)

$$M_i = \frac{q_i}{q_{i-1}} \quad (4)$$

where M_i is the multiplier of the current scenario

q_i is the simulation result of the current scenario under analysis (W/m^2)

q_{i-1} is the simulation result of the previous scenario under analysis (W/m^2)

The multiplier is based on the heat flux density values output by ANSYS. Equations (1) and (2) define how heat flux density is converted to thermal transmittance per unit area and of a given area therefore this multiplier can be applied to those terms as well. This also extends to other similar terms such as R-Value and RSI (in which you would divide the multiplier since R-value is the inverse of thermal transmittance). It should be noted that if this multiplier is applied to other terms, there is a small deviation due to the conversions, but the error is negligible.

Assembly Details

All 26 assemblies were first built in the SolidWorks software for dimensional accuracy and then imported into ANSYS for the 3D thermal finite element analysis. Overall assembly dimensions are shown in Table 1.

Table 1. Assembly Dimensions

	Full Wall Assembly
Overall Height (m)	2.623
Overall Length (m)	1.2
Concrete Slab Projection[1] (m)	0.8

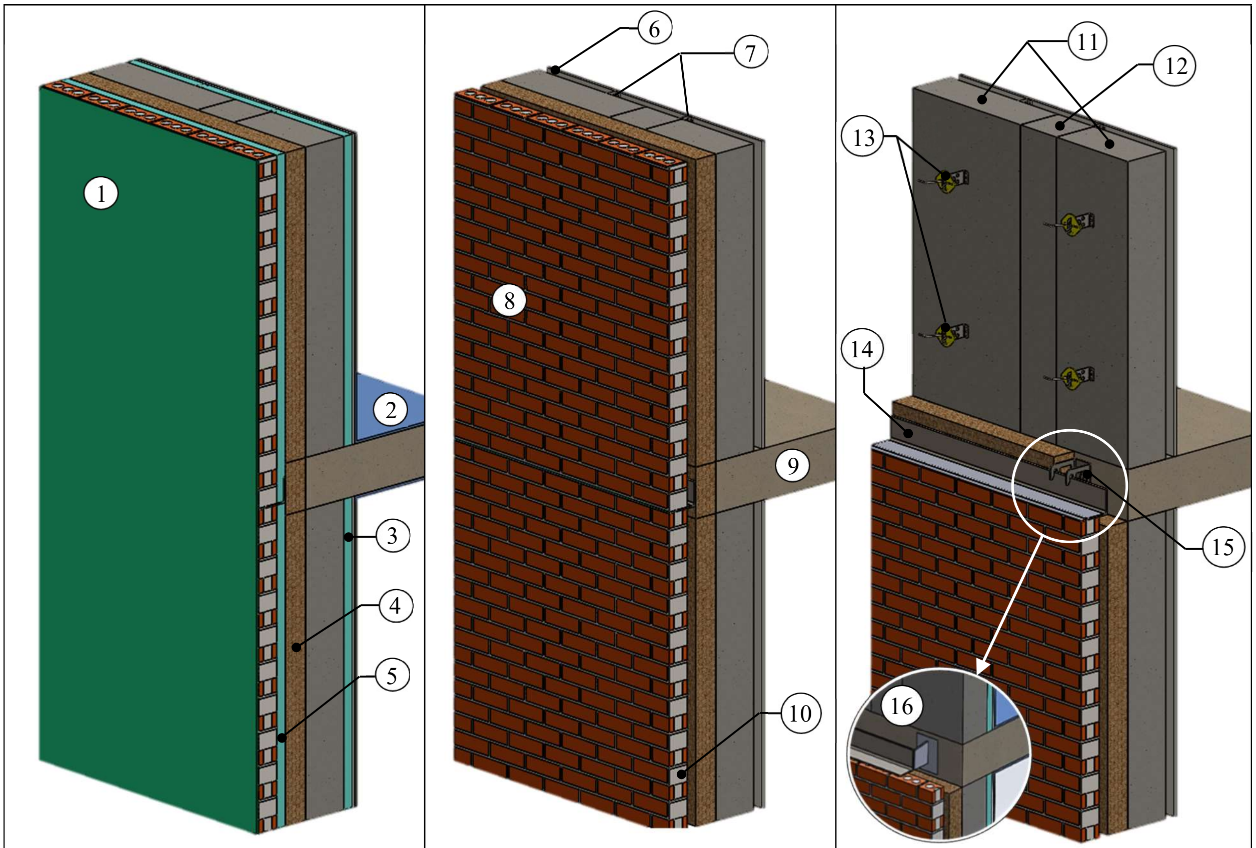
[1] Perpendicular to the face of the wall, towards the building interior.

Table 2 outlines the components in the assemblies, including component dimensions and their corresponding thermal properties. The manipulated variables in these models include four different insulation thicknesses: 101.6 mm (4”), 152.4 mm (6”), 203.2 mm (8”), and 254 mm (10”); two different types of stand-off shelf angle connectors: a proprietary bracket and traditional welded knife plates; 2 different knife plate materials: galvanized steel and GFRP; and frequency of spacing of the stand-off shelf connectors: 1.22 m (4’) and 0.610 m (2’). The proprietary bracket is not available in a GFRP material therefore only the knife plates are modeled using GFRP for the sake of thermal comparison only. The GFRP knife plates have not been structurally tested.

Table 2. Masonry Wall Components

Component	Insulation Thickness (mm)	Thickness (mm)	Conductivity (W/mK)
Interior Film	All	10	0.083
Gypsum Board	All	23	0.16
Air in Stud Cavity	All	92	0.57531
3 5/8” x 1 5/8” Steel Studs	All	20 gauge	62
Un-grouted Concrete Blocks	All	200	0.87
Grouted Concrete Blocks	All	200	1.13
Exterior Mineral Wool Insulation	All	102	0.034
Face-Mounted Masonry Ties (Hot-Dip Galvanized)	101.6	16 gauge	62
	152.4, 203.2, 254	3.175	
Intermediate Concrete Slab	All	203	1.8
Proprietary Bracket	All	4.76	50
Knife Plate	101.6	4.19 backer plate 9.53 knife edge	50 for galvanized steel 0.2 for GFRP
	152.4, 203.2, 254	4.19 backer plate 12.7 knife edge	
101.6 x 101.6 Shelf Angle	All	6.35	50
Vented Air Cavity	All	25	0.3571
Brick Veneer	All	92	0.78
Mortar	All	10	0.5
Exterior Film	All	10	0.34

Figure 1 provides a visual representation of the components outlined in Table 2. For clarity, some components have been hidden in a succession of steps.



Number	Component	Number	Component	Number	Component
1	Exterior Film	6	Gypsum Board	11	Un-Grouted Concrete Blocks
2	Interior Film	7	Steel Studs	12	Grouted Concrete Blocks
3	Air in Stud Cavity	8	Brick Veneer	13	Face-Mounted Masonry Ties
4	Mineral Wool Insulation	9	Concrete Slab	14	Shelf Angle
5	Vented Air Cavity	10	Mortar	15	Proprietary Bracket
				16	Knife Plate[1]

Figure 1. Full Masonry Wall Assembly and Components

[1] Shown as an alternative; assembly spliced where the knife plate meets the shelf angle, for clarity.

Assumptions and Simplifications

The concrete block backup was modelled as fully grouted in every 4th cell. To simplify the block geometry, the blocks were constructed as fully solid rectangular prisms with a nominal size of 400 mm x 200 mm x 200 mm (L x W x H). The mortar between the concrete blocks were neglected, but its geometry was accounted for within the wall assembly (i.e. 10 mm perimeter thickness was added to each block), but given concrete block properties. The entire back-up wall was modeled as 3 separate bodies: two un-grouted areas separated by a single grouted cell column. The location of the 4th cell was given its own grouted concrete block thermal properties whereas the remaining blocks were given un-grouted concrete block thermal properties.

To account for the convective and radiative heat transfer on the interior and exterior surfaces, an interior and exterior film, each 10 mm thick, was placed along the surfaces of the assembly, with a thermal conductivity of 0.083 W/m°C and 0.34 W/m°C, respectively. These values were adapted from the contact resistances given in the 2009 ASHRAE Handbook – Fundamentals [5, 6].

Contact resistances were implemented between materials in the models, but only at the major areas such as the steel flanges at sheathing interfaces, insulation interfaces, and steel to concrete interfaces (neglecting masonry tie-to-concrete block backup interfaces). The contact resistance values were given by project report ASHRAE RP-1365 [6]. Masonry tie to concrete block backup and steel to steel contacts were neglected for model simplification. Note that by neglecting these contact resistances, the model becomes more conservative, although by an insignificant amount as the contact areas to the masonry ties are very small in comparison to the full model.

An indoor air temperature of 21°C and outdoor temperature of -18°C (a temperature difference of 39°C or K) was applied to all models, as per NECB 2017 and ASTM C 1363 [2, 7].

The knife plate geometry in this study was not structurally designed for the intended loads shown in the model. It is a generic detail that may not be structurally sufficient (especially for the thicker insulation sizes and for the knife plates fabricated using GFRP).

RESULTS

The results of the 3D thermal simulations can be found in Table 3 and Table 4 below.

Table 3. Simulation Results, Heat Flux Density q (W/m^2)

Stand-off Shelf Connector	Insulation Thickness (mm)	HDG Connector, 1220 mm (4') spacing	HDG Connector, 610 mm (2') spacing	GFRP Connector, 1220 mm (4') spacing	Clear Wall
Proprietary Bracket	101.6	11.39	13.03	N/A	7.78
	152.4	8.37	10.14		5.28
	203.2	6.75	8.37		4.39
	254	5.63	7.22		3.66
Knife Plate	101.6	11.92	12.86	10.59	7.78
	152.4	8.43	9.45	7.36	5.28
	203.2	6.74	7.71	5.72	4.39
	254	5.65	6.58	4.68	3.66

Table 4. Simulation Results, Linear Transmittance ψ (W/mK)

Stand-off Shelf Connector	Insulation Thickness (mm)	HDG Connector, 1220 mm (4') spacing	HDG Connector, 610 mm (2') spacing	GFRP Connector, 1220 mm (4') spacing
Proprietary Bracket	101.6	0.24	0.35	N/A
	152.4	0.21	0.33	
	203.2	0.16	0.27	
	254	0.13	0.24	
Knife Plate	101.6	0.28	0.34	0.19
	152.4	0.21	0.28	0.14
	203.2	0.16	0.22	0.09
	254	0.13	0.20	0.07

Comparison

A comparison between the configuration (cross-sectional geometry) of the stand-off shelf angle connectors was investigated first. The two stand-offs investigated were the proprietary bracket system and conventional knife plates. In terms of thermal performance at a 610 mm (2') spacing, the difference between the two systems is almost negligible, ranging between 0.12 to 4.48%, with the effect becoming less prominent as insulation thickness increases. This is reinforced in Table 4, where the ψ value for insulation sizes beyond 101.6 mm (4") are identical. Although proprietary products often have a higher initial cost than conventional systems, it should be noted that using knife plates requires an engineer for design procurement and hiring additional welders on-site for installation. On site welding has additional risks including pitting of glazing and other surfaces, and fire. Proprietary shelf angle bracket systems provide the benefit that the design cost is either included in the cost or is "tabled", is prescriptive in nature given pre-engineering and often easier to install.

In Table 3 it can be seen that changing the knife plate material from HDG steel to GFRP has a greater effect on thermal performance than changing the stand-off configuration. The difference appears to be more significant as the insulation thickness increases, with improvements in the thermal performance ranging from 11.16% with a 102 mm insulation thickness to 17.17% with a 254 mm insulation thickness.

Stand-off spacing appears to have the greatest range in improvement on thermal performance. While increasing insulation thickness, reducing the stand-off spacing from 1.22 m (4') to 0.610 m (2') increases the heat flux density and reduces the thermal performance by 12.61 to 22.02% and 7.30 to 14.19% for the proprietary brackets and knife plate system, respectively.

Table 5 presents the multipliers that were obtained from each scenario. These multipliers are meant to be applied to scenarios that go beyond the models presented in this paper. Scenario A is labeled *Insulation*^{1,2}. This indicates that the manipulated variable is the insulation thickness, and the constant variable is the 1.22 m (4') spacing along with the HDG stand-off connector, as indicated in the superscript. It is known that as the amount of insulation increases, the heat flux density of the assembly decreases - a pattern that can be noted in Table 3. Taking this into account, the multipliers shown in the table are applied to the scenario with a heat flux density of higher value (thus smaller insulation thickness) to resolve the heat flux density of the next insulation thickness size. Scenario B labeled *Insulation*[1,3] is taken the same as the previous scenario, but with GFRP connectors for the knife plate system. It should be noted that the multiplier should be accounted for by the amount of times the insulation increases by 50.8 mm (2”).

Scenario C looks at the difference between using HDG and GFRP stand-off connectors within each insulation size. It is also known that GFRP material has a lower conductivity than HDG steel, thus reducing the overall heat flux density of the assembly, which is also seen in Table 3. Therefore, the multiplier in the third scenario is applied to the HDG assembly to resolve the GFRP assembly.

The fourth scenario compares the 1.22 m (4’) spacing and 0.610 m (2’) spacing for each insulation size. Here, it is obvious that the reduced stand-off spacing (i.e. more stand-offs) would result in an assembly with a higher heat flux density. Thus, the multiplier for the fourth scenario is applied to the assembly with 1.22 m (4’) spacing to resolve the assembly with 0.610 m (2’) spacing.

Table 5. Multipliers for Thermal Estimation

Stand-off Shelf Connector	Insulation Thickness (mm)	Scenario			
		A	B	C	D
		Insulation[1,2]	Insulation[1,3]	HDG and GFRP connectors	1.22 m (4’) to 0.610 m (2’) spacing
Proprietary Brackets	101.6	0.73	N/A	N/A	1.14
	152.4	0.81			1.21
	203.2	0.83			1.24
	254	N/A			1.28
Knife Plate	101.6	0.71	0.69	0.89	1.08
	152.4	0.80	0.78	0.87	1.12
	203.2	0.84	0.82	0.85	1.14
	254	N/A	N/A	N/A	1.17

[1]At 1.22 m (4’) spacing.
[2]HDG stand-off shelf angle connectors used.
[3]GFRP stand-off shelf angle connectors used.

Based on the multipliers presented above, the values are close enough that an average value can be reasonably deduced to further simplify the process, see Table 6. By using an average multiplier, the same value is used for each category regardless of insulation thickness. For example, in Table 6, the multiplier in Scenario C would be applied to assemblies that need to change from HDG to GFRP knife plates only. Similarly, the multiplier in Scenario D would be applied to assemblies that has a reduction in spacing from 1.22 m (4’) to 0.610 m (2’) spacing for either knife plates or a proprietary bracket system. Again, for Scenario A and B, the multiplier should be accounted for by the amount of times the insulation increases by 50.8 mm (2").

Table 6. Average Multipliers for Thermal Estimation

<table>
<tr><td rowspan="3">Stand-off Shelf Connector</td><td rowspan="3">Insulation Thickness (mm)</td><td colspan="4">Scenario</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td>D</td></tr>
<tr><td>Insulation[1,2]</td><td>Insulation[1,3]</td><td>HDG and GFRP connectors</td><td>1220 mm (4') spacing to 610 mm (2')[2]</td></tr>
<tr><td rowspan="4">Proprietary Brackets</td><td>101.6</td><td rowspan="4">0.79</td><td rowspan="4">N/A</td><td rowspan="4">N/A</td><td rowspan="4">1.22</td></tr>
<tr><td>152.4</td></tr>
<tr><td>203.2</td></tr>
<tr><td>254</td></tr>
<tr><td rowspan="4">Knife Plate</td><td>101.6</td><td rowspan="4">0.78</td><td rowspan="4">0.76</td><td rowspan="4">0.87</td><td rowspan="4">1.13</td></tr>
<tr><td>152.4</td></tr>
<tr><td>203.2</td></tr>
<tr><td>254</td></tr>
</table>

[1]At 1.22 m (4') spacing.
[2]HDG stand-off shelf angle connectors used.
[3]GFRP stand-off shelf angle connectors used.

Example Calculations

(1) A ψ value of 0.26 W/mK is available for an assembly with 101.6 mm (4") of mineral wool insulation. The project under investigation requires 203.2 mm (8") of mineral wool insulation to meet code. Proprietary brackets with a HDG finish have been selected.

$$\psi_{final} = \psi_{given} \times M^2_{Scenario\ A}$$

$$\psi_{final} = 0.26\frac{W}{mK} \times 0.79^2 = 0.16$$

(2) The knife plate spacing of an assembly must be reduced from 1.22 m on center to 0.610 m to be able to support the vertical loads imposed on the system. The ψ value for a system with 101.6 mm of mineral wool insulation and 1.22 m on center spacing for knife plates has been found to be 0.36 W/mK. The project also requires 152.4 mm of mineral wool insulation.

$$\psi_{final} = \psi_{given} \times M_{Scenario\ A} \times M_{Scenario\ D}$$

$$\psi_{final} = 0.36\frac{W}{mK} \times 0.78 \times 1.13 = 0.32$$

CONCLUSION

A total of 26 3D models were simulated under steady-state thermal analysis conditions using the commercially available 3D finite element analysis ANSYS software. A concrete block back-up wall was used in all 26 cases. These models focused on varying insulation thickness, shelf angle stand-off configuration, stand off material, and stand-off spacing. The purpose of this study was to find a numerical relationship that can be applied to other assembly types based on these parameters, to avoid having to perform 3D computer simulations every time. These values provide an initial baseline for predicting linear thermal transmittance values at floor level when different scenarios are applied to a concrete block brick veneer wall. The proposed multiplicative factors are an average of all of the simulations and can be applied to values such as heat flux density, thermal transmittance per unit area, thermal transmittance of a given area, linear transmittance, R-value, and RSI.

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