DYNAMIC EFFECT OF THERMAL BRIDGES ON THE ENERGY DEMAND OF RESIDENTIAL BUILDINGS IN BRITISH COLUMBIA

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ABSTRACT

The commonly used approach to implement thermal bridging in whole building energy modeling is to adjust the insulation level such that the thermal transmittance of the wall will be equal to the effective overall U-value of the envelope details with thermal bridges. This approach does not take into account the dynamic effect of thermal bridges. This paper focuses on evaluating the dynamic effect of thermal bridges on the space heating and cooling energy demand of a typical multi-unit residential building (MURB) built in British Columbia through simulations. The parameters investigated include 1) four cities representing four climatic zones (zones 4-7); 2) two construction types, i.e. pour-in-place concrete and brick veneer with Concrete Masonry Unit; 3) two levels of thermal bridges, i.e. standard and improved design; 4) seven typical junction details; and 5) two modeling approaches, i.e. dynamic 3D modeling and the equivalent U-value method.

Simulation results show that the equivalent U-value method can underestimate the annual space heating energy demand by up to 13% for the pour-in-place concrete construction with standard connection details. The impact of dynamic effect of thermal bridges in brick veneer construction is less significant due to smaller area of thermal bridges. The difference between 3D dynamic modeling and the equivalent U-value method is reduced to less than 3% when the connection details are improved. These results indicate the importance of minimizing thermal bridges, which not only reduce the annual space heating energy demand but also reduce the error in modeling energy performance by the commonly used simple method. Therefore, more effort should be placed on designing building envelopes with improved connection details to eliminate thermal bridges, especially when higher insulation levels and better windows are used. It is equally important for all climates to minimize thermal bridges in building envelope design.

Keywords: dynamic effect of thermal bridges, Multi-unit Residential Buildings (MURB), whole building energy modeling, 3D modelling of thermal bridges, equivalent U-value method.

INTRODUCTION

To achieve high performing low-energy buildings, the design and performance of building envelopes is critical. Thermal bridges created by the discontinuity of thermal insulation have significant effects on the thermal performance of building envelopes. Thermal bridging at interfaces, such as slabs, parapets and glazing transitions, can be sources of significant heat loss in the winter and heat gain in the summer. Reduced interior surface temperatures due to thermal bridges can increase risk of condensation and mold growth in the winter time. Studies have shown that in some buildings up to 50% of the elevation area consists of three-dimensional envelope structural details as thermal bridges (Kosny and Desjarlais, 1994) and that up to 38%

of the heating energy can be lost through thermal bridges for well-insulated residential buildings with high performance windows and highly insulated walls and roofs (Theodosiou and Papadopoulous, 2008; Erhorn, 2010; Berggren and Wall, 2013; Theodosiou et al., 2015).

The effect of thermal bridges on the energy performance of buildings is typically evaluated through whole building energy modeling using the equivalent U-value method. The equivalent U-value method involves adjusting the insulation level of the one-dimensional multi-layered envelope component such that its thermal transmittance is equal to the effective overall U-value of the envelope detail with thermal bridges, while the material properties of the multi-layered component are kept unchanged. Therefore, the effect of thermal bridges on the overall thermal transmittance is taken into account, while the thermal inertia effect of the thermal bridges is ignored.

The presence of thermal bridges not only reduces the overall thermal resistance but also changes the dynamic characteristics of opaque walls, i.e. the amplitude and phase lag of admittance and transmittance of these walls (Mao and Johannesson, 1997). To account for the dynamic effect of thermal bridges in energy modeling, the equivalent wall method was developed by Kossecka and Kosny (1997 and 1998) and used to generate conduction transfer functions for 20 common wall assemblies with connection details, which are included in EnergyPlus™ (Kossecka and Kosny, 2001). The equivalent wall method represents the thermal bridges by a 1-D multi-layered structure, which has the same dynamic thermal characteristics as the complex wall systems with thermal bridges, therefore, the thermal inertia effect can also be taken into account. The more accurate modeling approach would be the direct implementation of 2D or 3D connection details in the whole building energy modeling program, however, this approach requires greater computing capacities and increases the complexity. A study by Ge and Baba (2015) found that the annual heating energy demand of a two-storey residential building with the inclusion of thermal bridges modeled using 3D dynamic method in WUFI Plus is 8–13% higher than that modeled using the equivalent U-value method for Montreal.

Multi-unit residential buildings (MURBs) consist of one-third of the residential buildings and consume 40-50% of the energy used by the residential sector in Canada (NRCan, 2008). A study by Ge et al. (2013) showed that for a typical high-rise MURB building, a balcony cross-section area representing 4% of the total exterior wall may contribute up to 11% of the space heating energy consumption depending on the thermal performance of windows and the opaque walls. Ignoring the dynamic effect of the concrete balcony of this building using the simplified equivalent U-value method can underestimate the space heating energy demand by up to 15% (Baba and Ge, 2016).

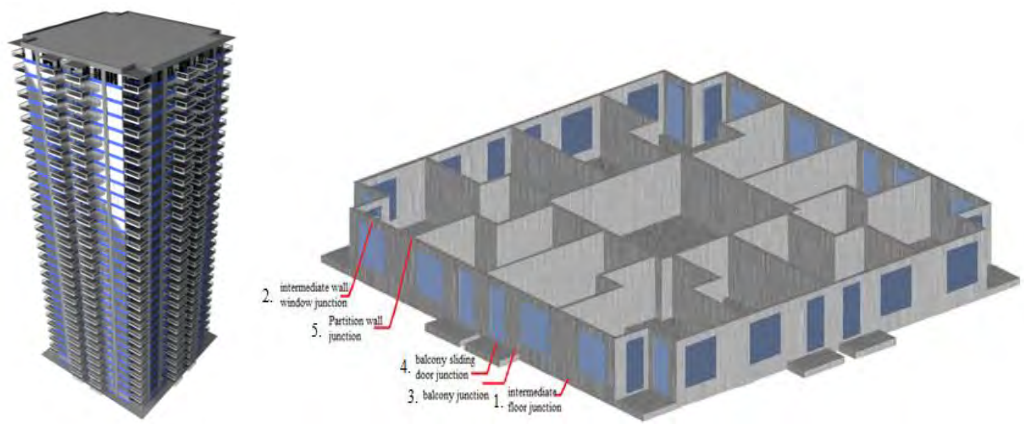
The province of British Columbia recently introduced the Energy Step Code (2016) for voluntary use as a measure to guide the industry to achieve consistent energy efficiency improvement from current building codes to net-zero energy ready buildings by 2030. To achieve this goal, emphasis is placed on comprehensive and stringent requirements on building envelope performance including the connection details. Given the increased importance of thermal bridges for better insulated building envelopes, how the simplified thermal bridging model approach using the equivalent U-value method impacts the accuracy of energy performance prediction requires further investigation. The objective of this paper is to evaluate the dynamic effect of thermal bridges on the energy demand of typical MURBs built in BC's climates. In this study, the equivalent U-value method and 3D dynamic modeling method were used to implement thermal bridges in whole building energy simulation programs.

METHODOLOGY

The dynamic effect of thermal bridges represented by typical junction details on the annual space heating and cooling energy demand is evaluated through simulations on a typical MURB with high thermal mass. The effects of two thermal bridging modeling methods, namely, equivalent U-value method and 3D dynamic modeling, on the energy performance of the case study building are compared. The following sections present the case study building, the two modeling methods implemented, and the simulation scenarios studied.

Case Study Building

The sketch up of the case study building is shown in Figure 1. This archetype building represents a typical MURB built in recent years in British Columbia (BC) of Canada. The selected building has 30 floors with a window wall ratio of 40%. The gross floor area of the building is 27,871 m2 and its length to width ratio is 1:1 and wall to roof ratio is 10.8:1, respectively.



a) b)

Figure 1: a) Sketch up of the case study building; b) 3D representation of a typical floor with thermal bridge locations. Dimension in m (adapted from BC Hydro Power Smart, 2014)

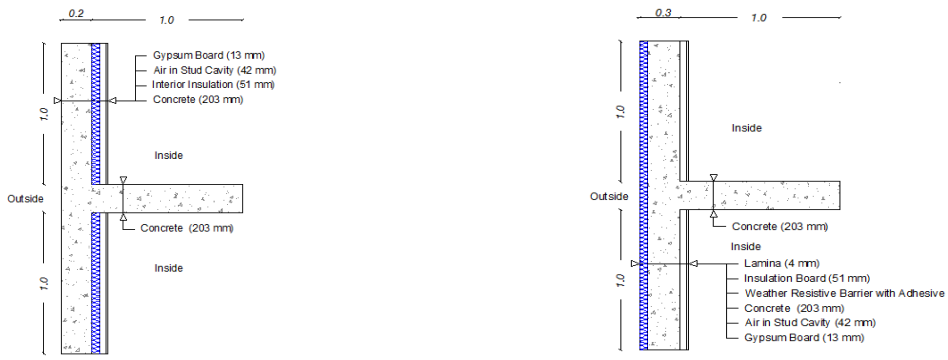
Typical Thermal Bridge Junctions

Two construction types with high thermal mass are considered for the case study building, i.e. pour-in-place concrete with interior insulation and brick veneer with concrete masonry unit (CMU). The typical thermal bridge junctions identified in this building include 1) intermediate floor junction; 2) intermediate wall/window junction; 3) balcony junction; 4) balcony sliding door junction; 5) partition wall junction; 6) roof junction; and 7) below-grade wall junction. Two levels of thermal bridging designs are considered for each junction, namely, standard and improved designs.

In the concrete construction, the strategy typically used to minimize thermal bridges at connections is to move the interior insulation to the exterior of the structural element. In the improved design, thermal insulation is placed on the exterior side of the pour-in-place concrete construction. The balcony thermal bridges can be improved by adding an insulated balcony separator as the thermal break. The separator is composed of an 80 mm thick expanded polystyrene (EPS) module to be inserted between the floor slab and balcony cantilever slab. Stainless steel tension and shear reinforcement bars pass through the EPS to allow

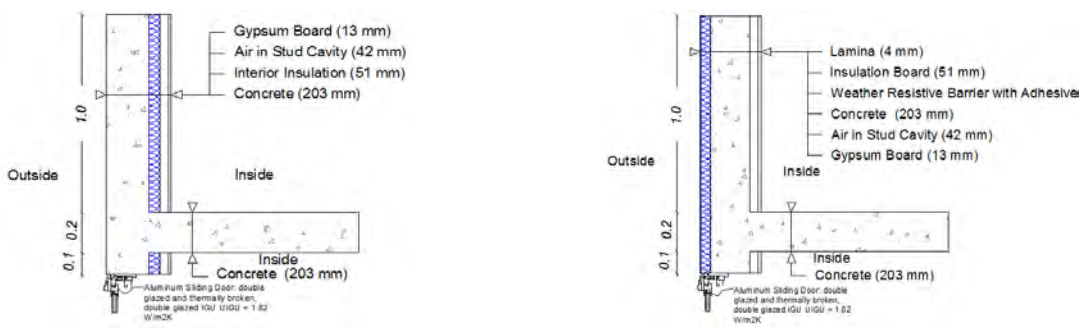
forces to be transferred from the balcony to the floor slab, but replacing the concrete volume with insulation significantly reduces heat flow through this thermal bridge.

In the brick veneer CMU construction, the standard design has insulation placed on the exterior side of the CMU backup wall and the main thermal bridges are present at the connection between shelf angle and the concrete floor slab. Therefore, in the improved design, the continuity of the exterior insulation at the slab/shelf angle connection is achieved by the use of offset shelf angle. The pour-in-place concrete connection details and brick veneer connection details are shown in Figure 2 and 3, respectively.



a). standard **b). improved**

Connection detail 1: Intermediate floor junction

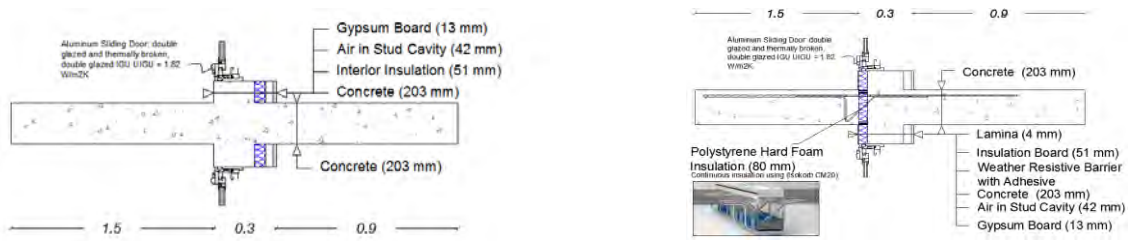


a). standard **b). improved**

Connection detail 2: intermediate window/wall junction

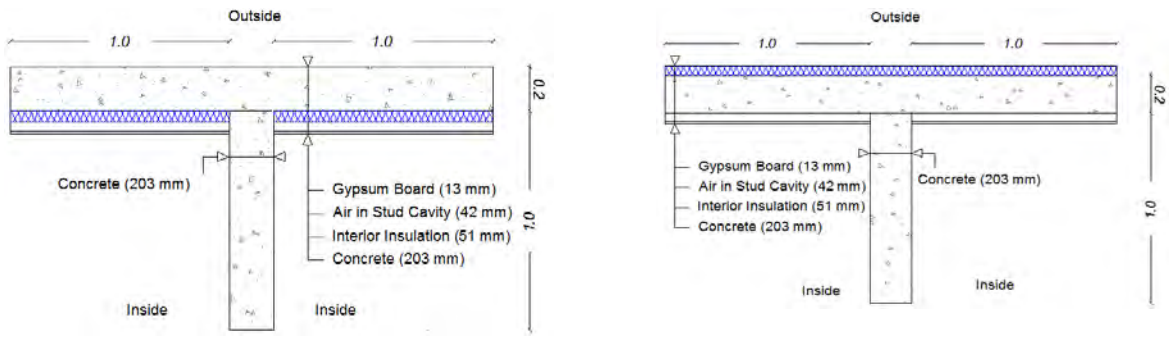
a). standard **b). improved**

Connection detail 3: balcony junction



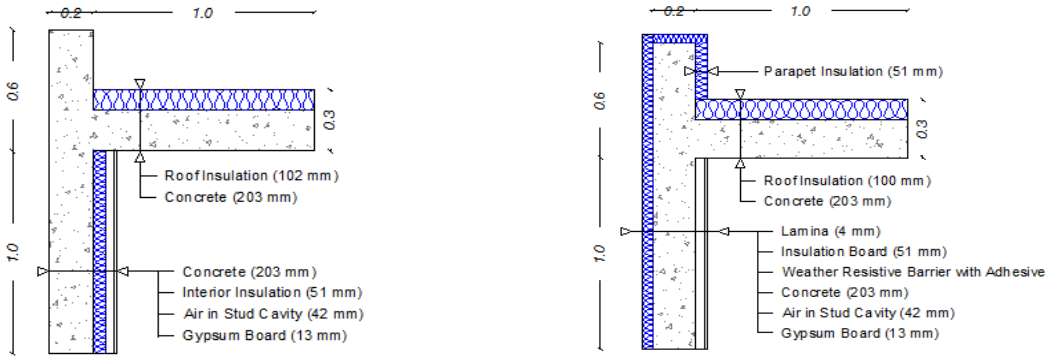
a). standard **b). improved**

Connection detail 4: balcony/sliding door junction



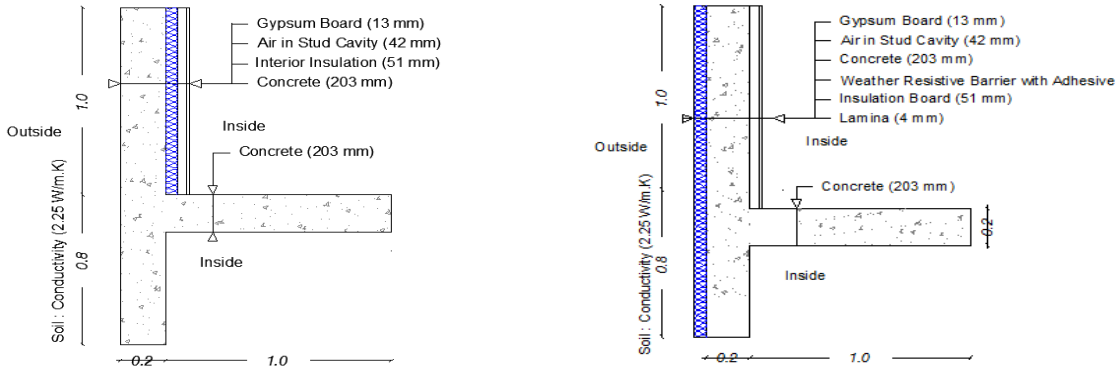
a). standard **b). improved**

Connection detail 5: partition wall junction (plan view)



a). standard **b). improved**

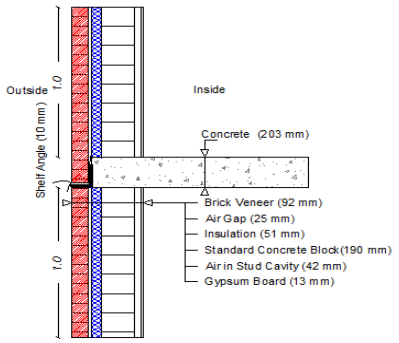
Connection detail 6: roof/wall junction



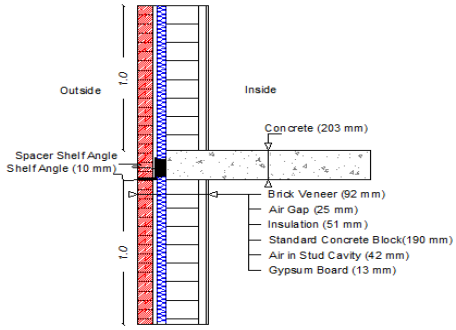
a). standard **b). improved**

Connection detail 7: below-grade wall junction

Figure 2: Seven thermal bridges in pour-in-place concrete construction. All dimensions in m.

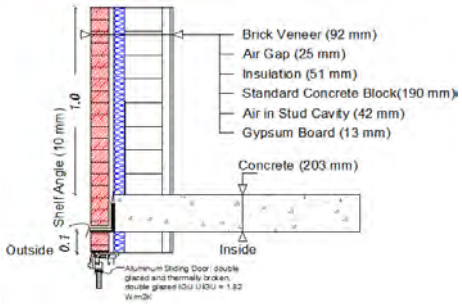


a). standard

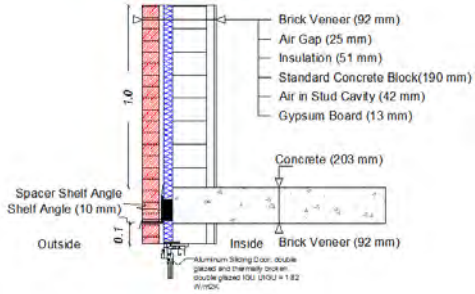


b). improved

Connection detail 1: Intermediate floor junction

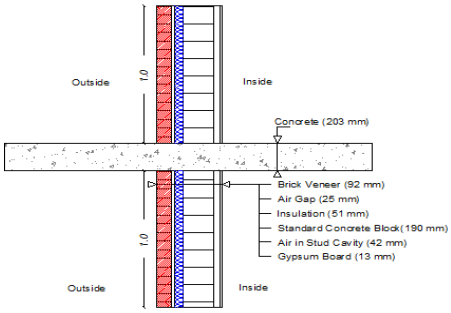


a). standard

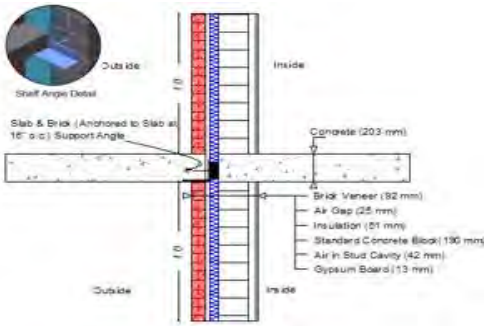


b). improved

Connection detail 2: intermediate window/wall junction

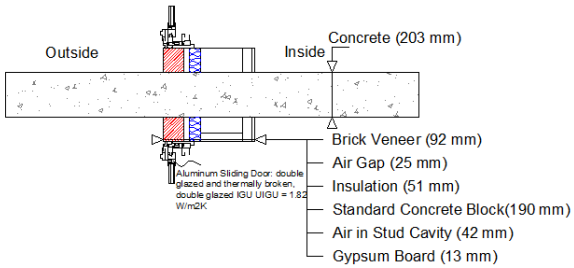


3 a). standard

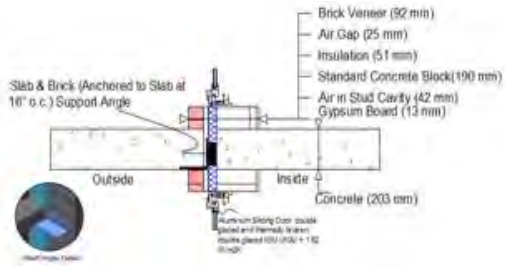


3 b). improved

Connection detail 3: balcony junction

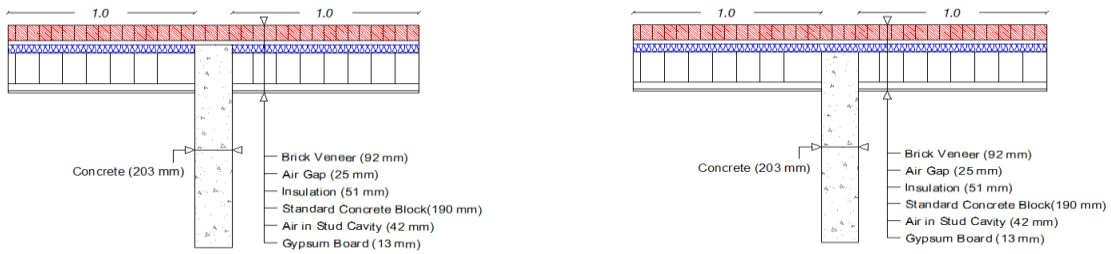


a). standard



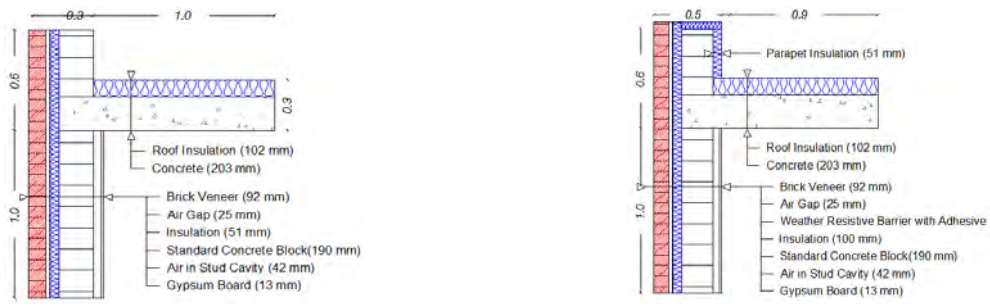
b). improved

Connection detail 4: balcony/sliding door junction



a). standard **b). improved**

Connection detail 5: partition wall junction (plan view)



a). standard **b). improved**

Connection detail 6: roof/wall junction

a). standard **b). improved**

Connection detail 7: below-grade wall junction

Figure 3: Seven thermal bridges in brick veneer CMU construction. All dimensions in m.

SIMULATION SCENARIOS

According to National Energy Code of Canada (2011), BC has climate zones ranging from Zone 4 to Zone 7. A typical city for each climate zone, Vancouver for zone 4, Summerland for zone 5, Prince George for zone 6 and Fort Nelson for zone 7, have been chosen for the simulations.

Two insulation levels, one meeting ASHRAE 90.1-2010 requirements, the second representing a higher insulation level, which has an overall thermal transmittance 20-45% (depending on the climatic zones) lower than the National Energy Code of Canada 2011 required, are included in the thermal bridge details to investigate the impact of thermal insulation levels on the dynamic effect of thermal bridges. Under the steady-state, the increase of insulation will amplify the thermal bridging effect and further degrades the effect of insulation on the effective overall U-value. The dynamic effect of higher insulation level of the thermal bridges needs to be studied.

Three levels of thermal bridges are evaluated including cases without thermal bridges, cases with the seven

standard connection details, and cases with the seven improved connection details, as shown in Figures 2 and 3. The case modeled without thermal bridges establish the baseline to demonstrate the contribution of thermal bridges to heating and cooling demand of the building.

In total 72 cases are modeled and the scenarios simulated are summarized in Table 1.

Table 1: Simulated scenarios

Parameters	
Thermal bridge levels	• No thermal bridges • Standard connection details • Improved connection details
Insulation level	• Standard construction meeting building codes • Higher level of insulation
Thermal bridge modeling approaches	• Direct 3D dynamic modeling • Equivalent U-value method
Climates	• Four climatic zones: 1. Vancouver (zone 4) 2. Summerland (zone 5) 3. Prince George (zone 6) 4. Fort Nelson (zone 7)

3D Dynamic Modeling Method

WUFI Plus provides the possibility to draw 3D thermal bridges directly into the building. Four steps are used to model the seven different junctions. The first step is to identify the thermal bridges and its quantities in 3D-object list. The second step is to determine the dimensions of each junction by x, y and z axis to draw the thermal bridge junctions and then select the materials for each junction. The fourth step is to link the thermal bridges with the zones in the whole building by determining the interior and exterior boundary conditions. To avoid counting the portion of the walls that have already been modelled in the 3D object twice, the net volume of the whole building needs to be calculated excluding this portion of the walls.

Equivalent U-Value Method

The different junctions are modelled in THERM 7.3 to calculate the effective overall thermal transmittance. The overall U-value obtained from THERM is used as the equivalent U-value for the implementation of thermal bridge junctions in WUFI Plus program. The sub-surfaces with various dimensions that have the same component layers as the 1-D building envelope component are added in WUFI Plus to represent the junctions. In these sub-surfaces, the physical properties and thickness of 1D wall components are kept unchanged except the thickness of thermal insulation layer, which is adjusted to achieve the effective U-value of the junction.

Table 2: Overall thermal transmittance (U-value in $W/m^2 \cdot K$) of pour-in-place concrete thermal bridge junctions obtained from THERM.

Junction	Standard insulation level				High insulation level	
	Climate zones 4-6		Climate zone 7		All zones	
	Standard	Improved	Standard	Improved	Standard	Improved
Intermediate floor junction	1.41	0.57	1.22	0.38	0.99	0.18

Intermediate wall/window junction	1.60	0.51	1.42	0.33	1.17	0.20
Balcony junction	1.51	0.51	1.32	0.32	1.10	0.18
Balcony sliding door junction	2.26	0.52	2.12	0.38	1.81	0.18
Partition wall junction	0.57	0.54	0.41	0.38	0.31	0.18
Below-grade wall junction	1.87	0.55	1.80	0.48	1.63	0.25
Roof wall junction	0.69	0.53	0.50	0.34	0.38	0.22
Roof slab junction	1.14	0.64	1.11	0.61	0.88	0.28

Table 3: Overall thermal transmittance (U-value in W/m^2·K) of brick veneer thermal bridge junctions obtained from THERM.

Junction	Standard insulation level				High insulation level	
	Climate zones 4-6		Climate zone 7		All zones	
	Standard	Improved	Standard	Improved	Standard	Improved
Intermediate floor junction	0.95	0.42	0.80	0.29	0.62	0.16
Intermediate wall/window junction	1.06	0.43	0.91	0.3	0.87	0.16
Balcony junction	1.16	0.44	1.02	0.31	0.89	0.**18**
Balcony sliding door junction	1.95	0.45	1.79	0.32	1.57	0.**44**
Partition wall junction	0.51	0.41	0.35	0.28	0.28	0.**18**
Below-grade wall junction	1.26	0.5	1.16	0.38	1.15	0.25
Roof wall junction	0.51	0.45	0.37	0.32	0.30	0.24
Roof slab junction	0.64	0.53	0.56	0.38	0.40	0.30

Settings in Whole Building Energy Simulations

In the whole building energy simulations, the heating set point is 21 ºC with a night setback temperature of 18 ºC (22:00-6:00) and the cooling set point is 25 ºC with a night setback temperature of 27 ºC (22:00-6:00) as per ASHRAE's 90.1 - User's Manual, Table G-G schedule (2010). Each floor is divided into five thermal zones, four perimeter zones according to the orientation, i.e. south, north, east, west, and one core zone for the corridor. The four perimeter zones include twelve apartments with an occupancy of 0.04 people/m^2. An infiltration rate of 0.25 L/s.m^2 through building envelope and a lighting power density of 8 W/m^2 is assumed.

RESULTS AND DISCUSSIONS

Space heating and cooling energy demand is used as the performance indicator to evaluate the effect of thermal bridges as the results of varying thermal bridge designs, insulation levels, and modeling approaches.

Annual Space Heating and Cooling Energy Demands with Standard Insulation Level

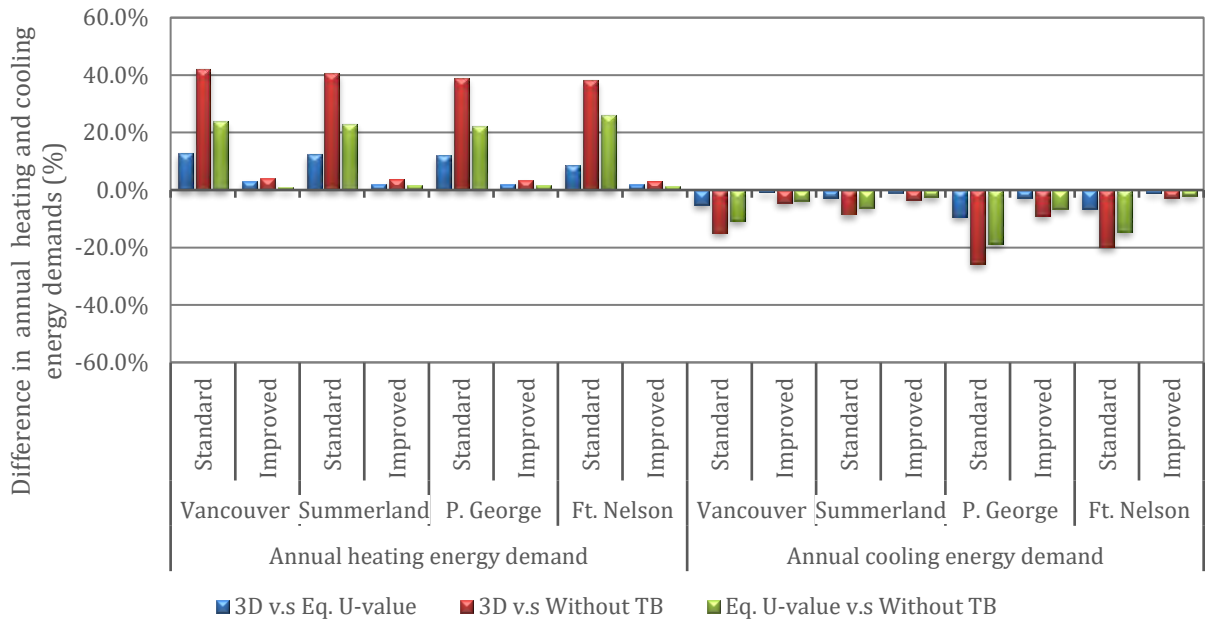
Figures 4 and 5 show the comparison of annual space heating and cooling energy demand in percentage difference between the cases with and without thermal bridges and the difference between the dynamic and equivalent U-value methods for pour-in-place concrete and brick veneer CMU, respectively. The annual space heating and cooling energy demand modeled without thermal bridges are used as the reference for calculating the percentage difference between the cases with and without thermal bridges. Also, the annual space heating and cooling energy demands modeled by the 3D method are used as the reference for calculating the percentage difference between the two modeling approaches.

Effect of Thermal Bridges on the Annual Space Heating and Cooling Energy Demand

As shown in Figure 4, the presence of the seven junctions as thermal bridges increased the annual space

heating energy demand of the building by 42.4% for Vancouver, 40.5% for Summerland, 38.9% for Prince George and 38.2% for Fort Nelson, respectively, when the 3D dynamic method is used. Fort Nelson is a city located in the coldest climatic zone among the four cities. Although the increase in space heating energy demand due to the thermal bridges (the case with thermal bridges compared with the case without thermal bridges) is higher for the colder climate (445.6 MWh in Fort Nelson v.s. 277.8 MWh in Vancouver), the percentage increase of the thermal bridge contribution is smaller for the colder climate (38.2% in Fort Nelson v.s. 42.4% in Vancouver, as shown in Figure 4) because of the higher annual space heating energy demand in Fort Nelson. In addition, the thermal insulation level prescribed by the building code for colder climates is relatively lower compared to those for milder climates. For example, the insulation level required by ASHRAE 90.1-2010 is the same for the roof for the four cities and similar for the wall insulation level for Vancouver, Summerland and Prince George. In the simulations, the same 1D wall and roof insulation level is assumed for the three cities except for Fort Nelson. Therefore, the assigned insulation level is relatively higher for Vancouver. The higher the insulation level, the more significant the thermal bridge contribution. Given that the four cities studied are in heating-dominant climates, the presence of thermal bridges under cooler temperatures especially during night in the summer help dissipate heat gained during the day, therefore, cooling needs are reduced by taking into account the effect of thermal bridges. The presence of thermal bridges reduced the annual space cooling energy demand by 14.8% for Vancouver, 8.4% for Summerland, 25.6% for Prince George, and 19.7% for Fort Nelson, respectively. Compared to heating energy demand, the space cooling energy demand is only a small portion of the space heating energy demand, ranging from 6% for Prince George to 30% for Summerland. The cooling energy demand is the highest for Summerland because of its particular climatic conditions. Among the four cities, Summerland has the highest design temperature in July and the highest annual solar radiation.

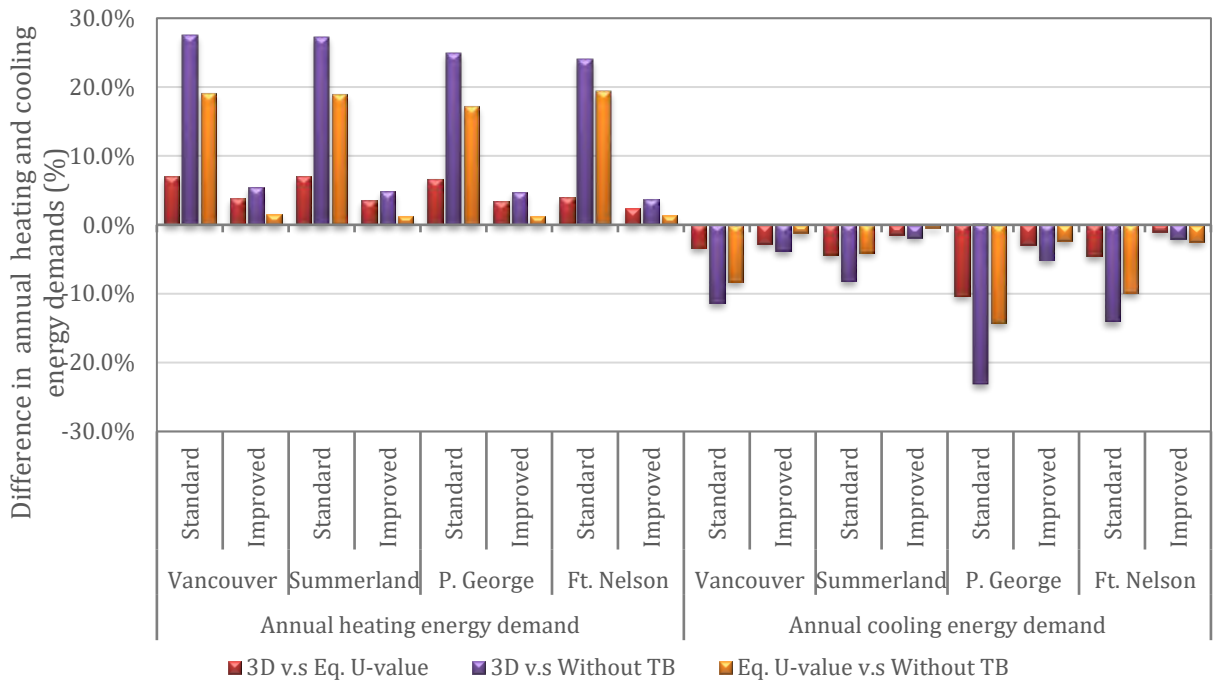
The improvement of connection details significantly reduced the contribution of these thermal bridges to the annual space heating energy demand of the building to 3.2% for Fort Nelson and to 4.0% for Vancouver. It also reduced the contribution of thermal bridges to the annual space cooling energy demand of the building to 4.4% for Vancouver, 3.3% for Summerland, 8.9% for Prince George, and 2.8% for Fort Nelson, respectively.



*TB-Thermal Bridge

Figure 4: Comparison of annual space heating and cooling energy demand in percentage difference between 3D modeling method and Eq. U-value method for the cases with and without thermal bridges for the concrete construction with standard insulation level.

Figure 5 shows that the presence of the seven junctions as thermal bridges in brick veneer construction increases the annual space heating energy demand of the building by 27.5% for Vancouver to 24.0% for Fort Nelson when the 3D dynamic method is used. Compared to the pour-in-place concrete construction, the contribution of thermal bridges are considerably lower in brick veneer CMU construction. Same as for the pour-in-place concrete construction, the percentage increase of the thermal bridge contribution is smaller for the colder climate (24.0% in Fort Nelson v.s. 27.5% in Vancouver, as shown in Fig. 5) because of the higher annual space heating energy demand in Fort Nelson and the relatively higher insulation level assigned for Vancouver. The improvement of connection details significantly reduced the contribution of these thermal bridges to the annual space heating energy demand of the building to 3.7% for Fort Nelson and to 5.5% for Vancouver. Same as for the concrete construction, the improvement of connection details reduces the impact of thermal bridges on the space cooling energy demand.



*TB-Thermal Bridge

Figure 5: Comparison of annual space heating and cooling energy demand in percentage difference between 3D modeling method and Eq. U-value method for the cases with and without thermal bridges for the brick veneer construction with standard insulation level.

Comparison Between 3D Dynamic Modeling and Equivalent U-value Methods

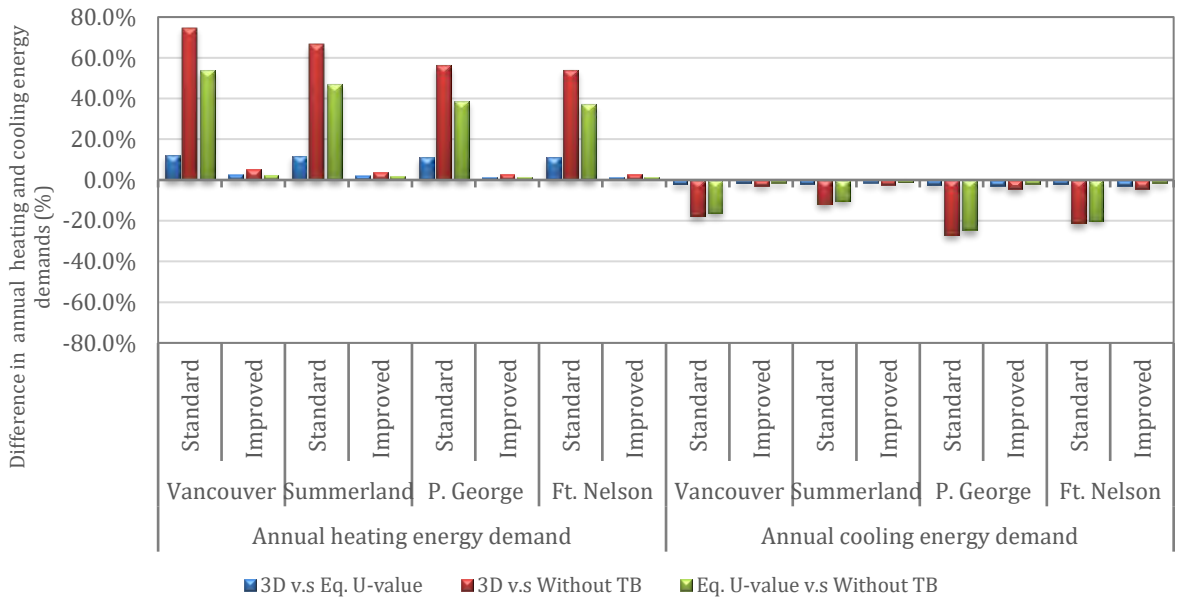
As shown in Figure 4, the space heating energy demands modeled by the 3D dynamic method are higher than those modeled using the equivalent U-value method. The difference between 3D dynamic and U-value method is 12.9% for Vancouver, 12.5% for Summerland, 12.0% for Prince George, and 8.8% for Fort Nelson, respectively. The milder the climate the higher the discrepancy, which is consistent with the observation made on the effect of thermal bridges to the space heating energy demand. As discussed earlier, the contribution of thermal bridges is slightly higher for milder climates, so is the dynamic effect of thermal bridges. As for the cooling energy demand, the modeling approach has a smaller impact, the difference between the 3D dynamic modeling and the equivalent U-value method ranges from 2.5% to 9.5%. The space cooling energy demand modeled by the 3D dynamic method is lower than that using the equivalent U-value and the equivalent wall methods. With the improvement of connection details, the dynamic effect reduces. The discrepancy between 3D dynamic modeling and the equivalent U-value method is reduced to 1.8-3.1% for space heating energy demand and 0.8-2.7% for space cooling energy demand, respectively.

As for the brick veneer construction (Figure 5), the difference between 3D dynamic and the equivalent U-value is reduced given that the brick veneer construction has less thermal bridges. The discrepancy in space heating energy demand ranges from 4.0-7.0% between 3D dynamic method and the equivalent U-value method for the four cities studied. Similar to the concrete construction, with the improvement of connection details, the dynamic effect slightly reduces. The annual space heating energy demands modeled by the 3D dynamic modeling are 2.4-3.8% higher than that obtained by the equivalent U-value method. As for the cooling energy demand, the difference between 3D and equivalent U-value method ranges from 1.0% to

2.8%.

Annual Space Heating and Cooling Energy Demands with High Insulation Level

Figures 6 and 7 show the comparison of annual heating and cooling energy demands in percentage difference between the cases with and without thermal bridges and the difference between the dynamic and equivalent U-value method for pour-in-place concrete and brick veneer CMU, respectively. The annual space heating and cooling energy demands modeled without thermal bridges are used as the reference for calculating the percentage difference between the cases with and without thermal bridges, and the 3D method are used as the reference for calculating the percentage difference between the two modeling approaches.



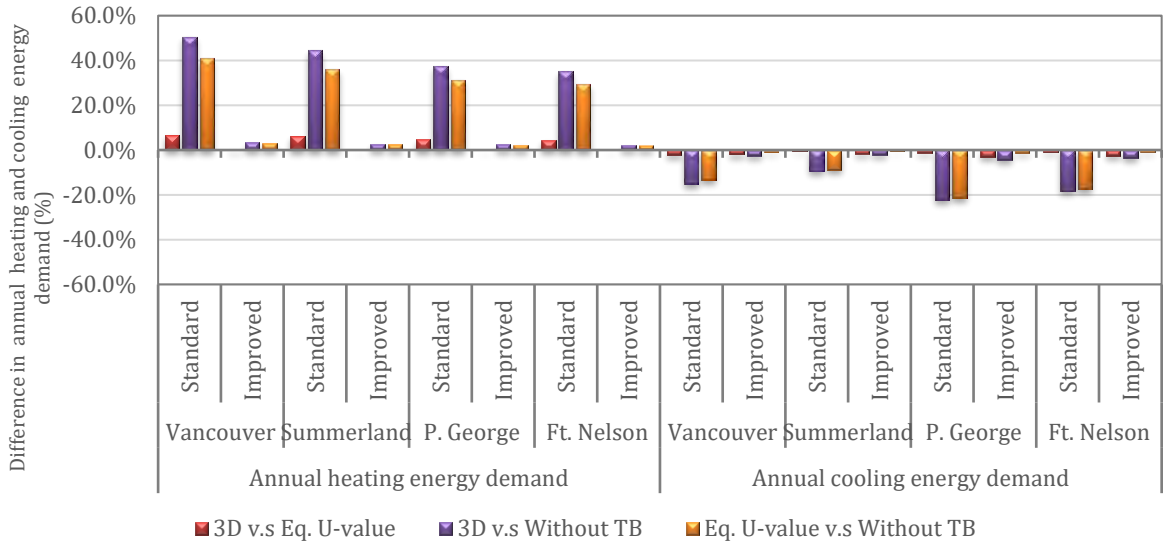
*TB-Thermal Bridge,

Figure 6: Comparison of annual space heating and cooling energy demand in percentage difference between 3D modeling method and Eq. U-value method and the cases with and without thermal bridges for the concrete construction with high insulation level.

Effect of Thermal Bridges on the Annual Space Heating and Cooling Energy Demands

As shown in Figure 6, with the increase of insulation level, the presence of thermal bridge junctions significantly increases the annual space heating energy demand of the building by 74.7% for Vancouver, 66.6% for Summerland, 56.1% for Prince George and 54.2% for Fort Nelson, respectively, when the 3D dynamic method is used. The impact of thermal bridges on space heating energy demands is more significant compared to the standard insulation level, at which the increase in annual space heating energy demand ranges from 38.2% to 42.4% for the four cities. The presence of thermal bridges reduces the annual space cooling energy demand by 17.6% for Vancouver, 11.8% for Summerland, 26.8% for Prince George, and 21.2% for Fort Nelson, respectively, which are slightly higher than the cases with the standard insulation level. Similar to the cases with the standard insulation level, the improvement of connection details significantly reduces the contribution of these thermal bridges to the annual space heating energy demand of the building to 5.1% for Vancouver, 3.8% for Summerland, 2.9% for Prince George, and 2.7% for Fort Nelson, respectively. It also reduces the contribution of thermal bridges to the annual space cooling energy

demand of the building to 2.8% for Vancouver, 2.2% for Summerland, 4.5% for Prince George, and 4.1% for Fort Nelson, respectively. In general, the equivalent U-value underestimates the contributions of thermal bridges to space heating and cooling energy demands compared to 3D dynamic modeling method.



*TB-Thermal Bridge,

Figure 7: Comparison of annual space heating and cooling energy demand in percentage difference between 3D modeling method and Eq. U-value method and the cases with and without thermal bridges for the brick veneer construction with high insulation level.

Similar trends are observed for brick veneer construction. As shown in Figure 7, the inclusion of thermal bridges increases the annual space heating energy demand by 35.0% for Fort Nelson to 50.5% for Vancouver, when the 3D dynamic modeling method is used. The improvement of connection details significantly reduced the contribution of these thermal bridges to the annual space heating and cooling energy demands.

Comparison between 3d Dynamic Modeling and Equivalent U-Value Methods

As shown in Figure 6, the space heating energy demands modeled by the 3D dynamic method are higher than those modeled using the equivalent U-value method. Compared to the standard insulation level, the discrepancy between 3D dynamic modeling and the equivalent U-value is slightly reduced. The difference between 3D dynamic and the equivalent U-value method is 12.0% for Vancouver, 11.8% for Summerland, 11.1% for Prince George, and 11.0% for Fort Nelson, respectively. As for the cooling energy demand, the modeling approach has a smaller impact, the difference between the 3D dynamic modeling and the equivalent U-value method ranges from 1.9% to 2.4%. The space cooling energy demand modeled by the 3D dynamic method is lower than that using the equivalent U-value. With the improvement of connection details, the dynamic effect is reduced. The discrepancy in space heating energy demand is reduced to 1.4-2.6% between 3D dynamic modeling and the equivalent U-value method.

As for the brick veneer construction (Figure 7), the difference between 3D dynamic and the equivalent U-value is reduced given that the brick veneer construction has less thermal bridges. The discrepancy in space heating energy demand ranges from 4.3-6.7% between 3D dynamic method and the equivalent U-value method for the four cities studied. As for the cooling energy demand, the difference between the 3D and the

equivalent U-value method ranges from 0.4% to 2.2%. The space cooling energy demands modeled by the 3D dynamic method are lower than those obtained using equivalent U-value method. With the improvement of connection details, the dynamic effect of thermal bridges on the space heating energy demand significantly reduces. The annual space heating energy demands modeled by the 3D dynamic modeling are 0.2-0.5% higher than that obtained by the equivalent U-value method.

CONCLUSION

The dynamic effect of seven thermal bridges on the energy performance of a high-rise residential building is studied through simulations by comparing the simulation results using the equivalent U-value method with those obtained using 3D dynamic modeling approach. The annual space heating and cooling energy demands are used as performance indicators to evaluate the dynamic effect of thermal bridges. Simulation results show that:

- The dynamic effect of thermal bridges on the energy performance (difference between 3D dynamic modeling and the equivalent U-value method) depends on the quantity and quality of thermal bridges.
    - The equivalent U-value method can underestimate the annual space heating energy demand by up to 13%. The thermal bridges of the study building represent about 12% of the exterior envelope area. With the increase of thermal bridging area, the dynamic effect of thermal bridges will be also increased.
    - The difference between 3D dynamic modeling and the equivalent U-value method is reduced to less than 3% when the connection details are improved. These results indicate the importance of minimizing thermal bridges, which not only reduces the annual space heating energy demand and energy consumption but also reduces the error in modeling energy performance by the commonly used simple method.
- With the increase of insulation level, the contribution of thermal bridges to the energy consumption significantly increases, while the dynamic effect of thermal bridges slightly decreases.
- It is observed that the dynamic effect of thermal bridges is slightly more significant (in term of percentage difference) for milder climates in space heating energy demand calculation due to the fact that the insulation levels for milder climates are relatively higher than those specified for colder climates by building codes and used in simulations. The higher the insulation levels, the greater the contribution of thermal bridges. Therefore, it is equally important for all climates to minimize thermal bridges in building envelope design.
- Efforts should be placed on designing good building envelope connection details to minimize/eliminate thermal bridges especially when higher insulation levels and better windows are used, which not only reduces the energy consumption of buildings but also the errors in modeling the dynamic effect of thermal bridges using simplified method.

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