DYNAMIC EFFECT OF THERMAL BRIDGES ON THE ENERGY PERFORMANCE OF RESIDENTIAL BUILDINGS IN BC

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ABSTRACT

Thermal bridges in building envelopes contribute significantly to the heating energy consumption of residential buildings in Canada. The commonly used approach to implement thermal bridges in whole building energy modeling is the effective overall U-value method, which does not take into account the dynamic effect of thermal bridges.

The objective of this paper is to investigate the dynamic effect of thermal bridges on the energy performance of multi-unit residential buildings under British Columbia's climates. Two methods, i.e. dynamic 3D modeling method and the equivalent U-value method, are used to implement thermal bridge junctions in WUFI Plus program. A 30 storey pour-in-place concrete building is chosen as a case study with different types of junctions. The results show that the inclusion of different thermal bridge junctions increases the annual heating energy load by 37.4-42.2% of this building. Compared to the dynamic 3D modeling method, the annual heating energy loads are underestimated by 12.5-14.8% using the equivalent U-value method.

Keywords: dynamic effect of thermal bridges; equivalent U-value method; energy performance, residential buildings, building envelopes.

INTRODUCTION

Buildings need to be energy efficient, durable and provide a healthy and pleasant indoor environment. Increasing the suitable insulation in the building envelope components can reduce energy consumption and improve the building's durability. However, thermal bridges that are created by the discontinuity of thermal insulation can cause 40% of the building envelope damages [1] and may increase the energy consumption by up to 30% [2,3]. To minimize the effect of thermal bridges on the building energy performance and durability, building standards and codes set up requirements and guidelines to deal with thermal bridges by imposing a limit on the linear or point thermal transmittances of thermal bridges within the building envelope, such as the European Standard EN ISO 14683 [4] in European countries, or by mandating a maximum effective thermal transmittance (U-value) in North America, such as the National Energy Code of Buildings in Canada [5] or ASHRAE 90.1 [6].

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 is to adjust 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. An improvement on the equivalent U-value method is the Combined Thermal Properties (CTP) method introduced by Purdy and Beausoleil-Morrison [7]. The CTP method involves adjusting the thermal conductivity of the composite layer (insulation with frame) to match the total thermal resistance of the structure with thermal bridges. The density and specific heat of this composite layer is also adjusted to match the thermal mass of the frame and insulation to account for the thermal mass effect although it may not represent the actual dynamic thermal behavior. This method is only applicable to thermal bridges created by repetitive structural members within the building envelope assemblies.

To account for the dynamic effect of thermal bridges in energy modeling, the equivalent wall method was developed by Kossecka and Kosny [8, 9] The equivalent wall method is to represent 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. However, a difference between the equivalent wall method and hot box measurement was noticed by Kosny and Kossecka [10]. The more accurate modeling of thermal bridges would be the direct implementation of 2D or 3D connection details in the whole building energy modeling program, however, the direct 2-D or 3-D modeling of thermal bridges in whole building energy simulation programs requires greater computing capacities and increases the complexity. Déqué et al. [11] used a two-stage approach to firstly model two types of 2D thermal bridge geometries using the state space technique and then the reduced dynamic wall model was implemented in an energy modeling program. They found that the detailed dynamic simulation of 2D thermal bridges can increase the accuracy of heat loss by 5–7% compared to a steady-state simulation that was represented by statutory tabulated values.

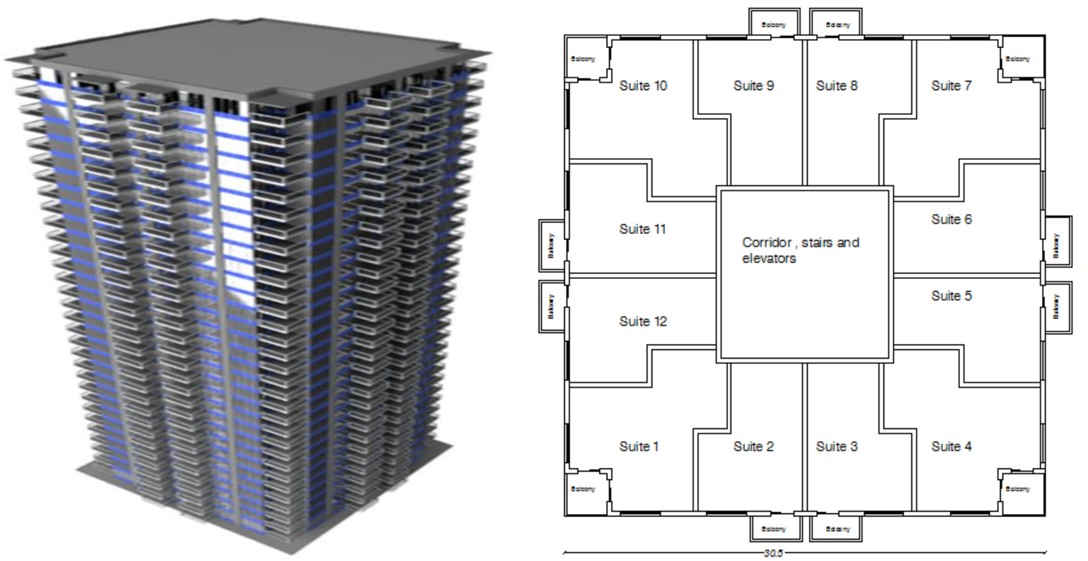
Despite the significant impact of thermal bridges on building energy consumption, the Canadian building codes do not have elaborate requirements of thermal bridges. The 2011 National Energy Code of Canada for Buildings [5] requires that the thermal bridging effect of repetitive structural members such as stud and joists, and of ancillary members such as lintels, sills and plates, to be accounted for in the calculation of effective thermal resistance of assemblies; however, minor penetration or minor structural members and major structural penetrations, such as balconies, with a cross-sectional area less than 2% of the penetrated wall area need not be taken into account in the calculation of the effective thermal resistance of the penetrated wall area. A study by Ge et al. [12] showed that for a typical high-rise multi-unit residential 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. A recent study on thermal bridges of typical constructions in the region of British Columbia showed that improved building envelope details minimizing thermal bridges can result in up to 10% energy savings, which is comparable to increasing insulation levels and using triple-glazing windows [13]. In these studies, the equivalent U-value method was used to implement thermal bridges in whole building energy simulation programs. A recent study by Ge and Baba [14] found that the annual heating load of a two-storey residential building with the inclusion of thermal bridges modeled using 3D dynamic method is 8–13% higher than that modeled using the equivalent U-value method for Montreal. For high-rise concrete buildings with more thermal bridges present at corners, partition walls in addition to the balcony, the dynamic effect may be more significant.

This paper investigates the dynamic effect of thermal bridges on the energy load of a typical high-rise residential building by comparing 3D dynamic modeling to the equivalent U-value method for two different climatic zones in British Columbia with two types of thermal bridging designs, i.e. poor and improved junctions.

METHODOLOGY

The dynamic effect of seven typical thermal bridge junctions (Fig. 2) on the annual heating and cooling load of a multi-unit residential building (MURB) (Fig. 1) is evaluated. 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) basement wall junction. Two levels of thermal bridging designs are considered for each junction, namely, poor and improved designs. The strategy tyically used to minimize thermal bridges at connections is to move the interior insulation to the exterior of the structural element. In the pour-in-place conrete construction, thermal insulation is placed on the exterior side of the concrete.

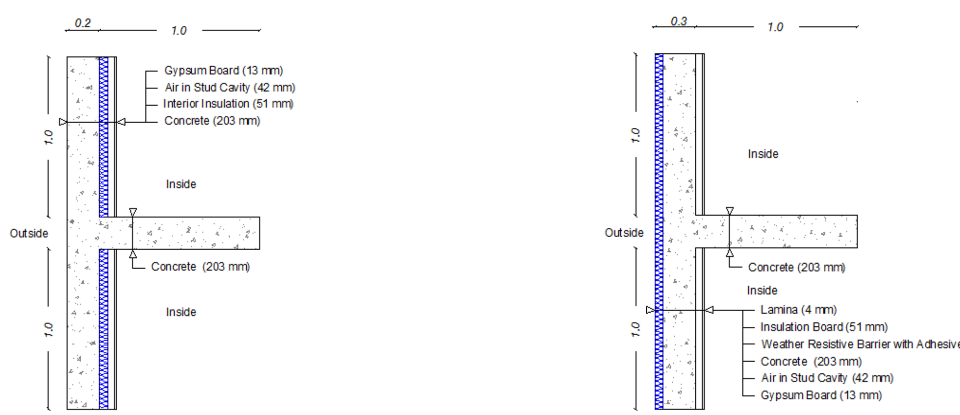
Two methods, i.e. 3D dynamic and equivalent U-value method, are used to implement thermal bridges in WUFI Plus, a whole building Heat, Air and Moisture modeling program [15]. The following sections provide a brief introduction of these two methods. Table 1 shows the physical properties of the construction materials.



a)

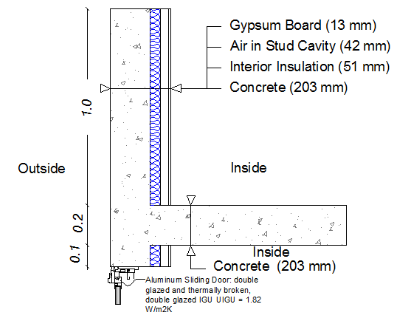
b)

Fig. 1. a) Sketch up of the high-rise building; b) A typical floor plan of the study building. Dimensions are in m.

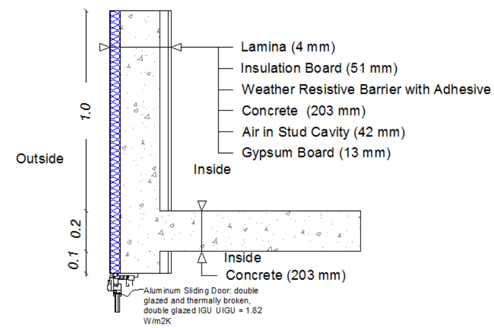


1 a). poor

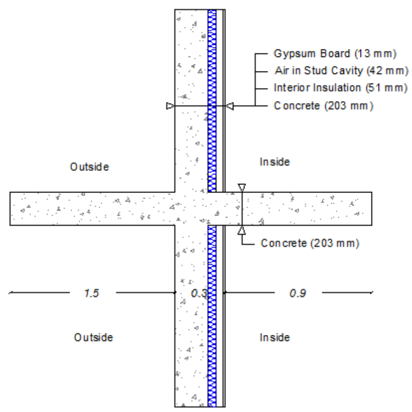
1 b). improved



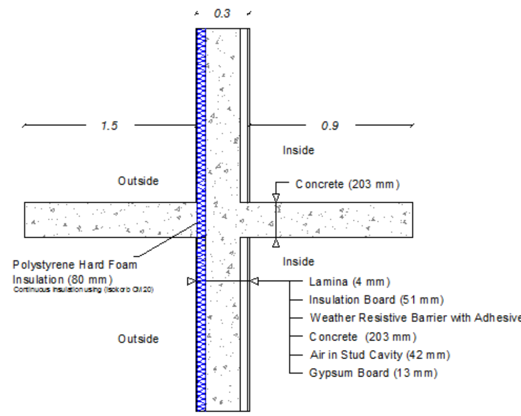
2 a). poor



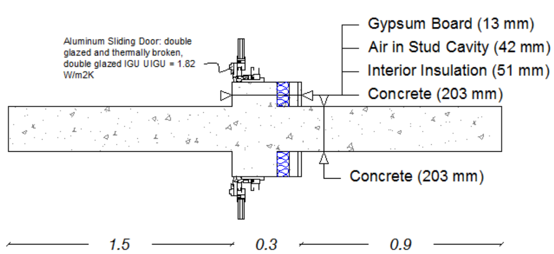
2 b). improved



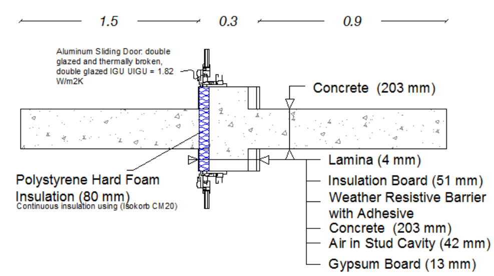
3 a). poor



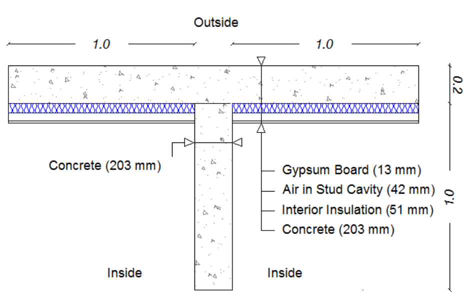
3 b). improved



4 a). poor



4 b). improved



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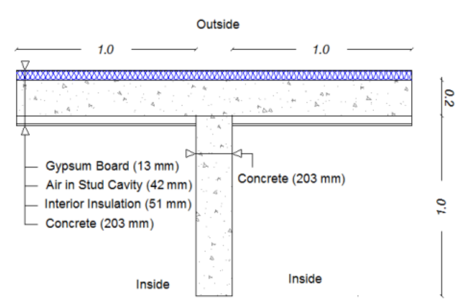
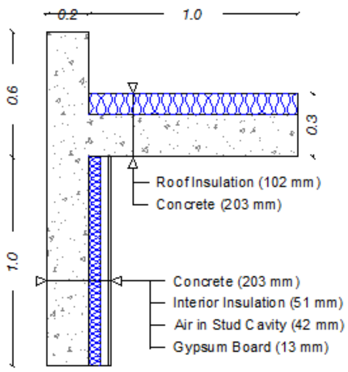
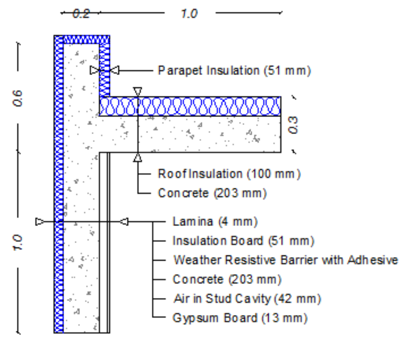


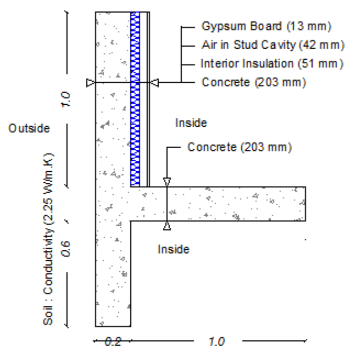
5 b). improved



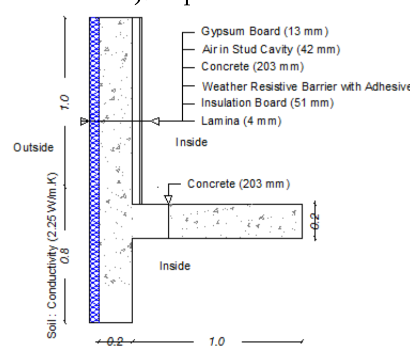
6 a). poor



6 b). improved



7 a). poor



7 b). improved

Fig. 2. Seven typical thermal bridges: 1. intermediate floor junction; 2. intermediate wall/window junction; 3. balcony junction; 4. balcony sliding door junction; 5. partition wall junction; 6. roof junction; 7. basement wall junction. All dimensions are in m.

Table 1. Thermal and physical properties of materials used in the pour-in-place concrete junctions

Materials	Thermal Conductivity (W/m K)	Density (kg/m^3)	Specific Heat (J/kg K)
Air in Stud Cavity	0.26	1.2	1000
Concrete	1.8	2250	850
Gypsum Board	0.16	800	1090
Insulation Board	0.039	16	1470
EPS insulation	0.03	28	1220
Lamina (4mm thick)	0.9	1922	850
Polystyrene hard foam insulation (thermal break)	0.031	1060	1500
Steel Stud (0.9 mm thickness and 16'' O.C)	62	7830	500

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 from the 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. THERM is a steady state 2D heat transfer program developed by Lawrence Berkeley National Laboratory. The overall U-value obtained from THERM is used as the equivalent U-value for the implementation of thermal bridge junctions in WUFI Plus. 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. The indoor temperature is set at 20^{o}C with a surface thermal resistance of 0.13 m^2·K/W for the vertical wall, 0.11 m^2·K/W for the horizontal roof slab and 0.17 m^2·K/W for the horizontal basement slab. The outside temperature is -18^{o}C with a surface thermal resistance of 0.04 m^2·K/W in the THERM analysis. Table 2 shows the overall U-value obtained for different junctions.

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

Junctions	Poor	Improved
Intermediate floor Junction	1.1	0.57
Intermediate wall/ window junction	1.6	0.51
Balcony Junction	1.71	0.51
Balcony sliding door junction	2.26	0.52
Partition junction	0.57	0.54
Basement wall junction	1.87	0.55
Roof wall junction	0.69	0.53
Roof slab junction	1.14	0.64

Climatic conditions

Vancouver, a city located in climatic zone 4, and Fort Nelson, a city location in climatic zone 7, are selected to study the dynamic effect of thermal bridges on the energy performance of this case study building.

For indoor condition in the whole building WUFI Plus simulations, the heating set point is 20^{o}C with a night setback temperature of 18^{o}C (22:00–06:00) and the cooling set point is 25^{o}C with a night setback temperature of 27^{o}C (06:00–22:00). An infiltration rate of 0.17ACH is assumed. The typical 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. These four perimeter zones include three suites with occupancy of 0.04 people/m^2 assumed. The effect of thermal bridges on the energy performance is evaluated by the annual heating and cooling loads.

RESULTS AND DISCUSSIONS

The annual space heating and cooling energy loads are compared for three cases as listed below:

- Case 1: thermal bridges in the high-rise building are modeled using 3D dynamic method
- Case 2: thermal bridges in the high-rise building are modeled using the equivalent U-value method.
- Case 3: thermal bridges in the high-rise building are not included in the whole building energy modeling.

Fig. 3 shows the percentage difference in annual heating and cooling loads among the three cases. The inclusion of poor thermal bridges through 3D dynamic modeling increases the annual heating load by 42.2% and 37.4% and reduces the annual cooling load by 14.8% and 17.4% although the cooling energy load is about 23% and 9% of space heating load for Vancouver and Fort Nelson, respectively, compared to the case without thermal bridges. Compared to the equivalent U-value method, the 3D dynamic modeling of thermal bridges results in about 14.8% and 12.5% increase in the annual heating load, while 4.8% and 4.7% reduction in the annual cooling load for Vancouver and Fort Nelson, respectively.

When the improved thermal bridges are implemented in 3D dynamic modeling, the inclusion of thermal bridges increases the heating loads by 4.0% for Vancouver and 3.4% for Fort Nelson and reduces the annual cooling by 4.0% for Vancouver and 5.1% for Fort Nelson. The difference in annual heating load between the 3D dynamic simulation and equivalent U-value is reduced to 3.1% and for Vancouver and 1.8% for Fort Nelson, respectively.

Table 3. Annual energy load for one typical floor with all junctions for two cities.

		Vancouver (zone 4)		Fort Nelson (zone 7)	
Implementation Methods		Annual heating load (kWh $\times 10^3$)	Annual cooling load (kWh $\times 10^3$)	Annual heating load (kWh $\times 10^3$)	Annual cooling load (kWh $\times 10^3$)
3D Modeling	Poor	25.2	5.8	49.5	4.7
	Improved	20.5	6.6	41.5	5.3
Eq. U-value	Poor	23.4	6.0	46.6	4.9
	Improved	20.1	6.7	40.9	5.4
Without TB	Poor	19.6	6.7	39.9	5.4
	Improved	19.4	6.8	39.7	5.5

*TB= Thermal bridge

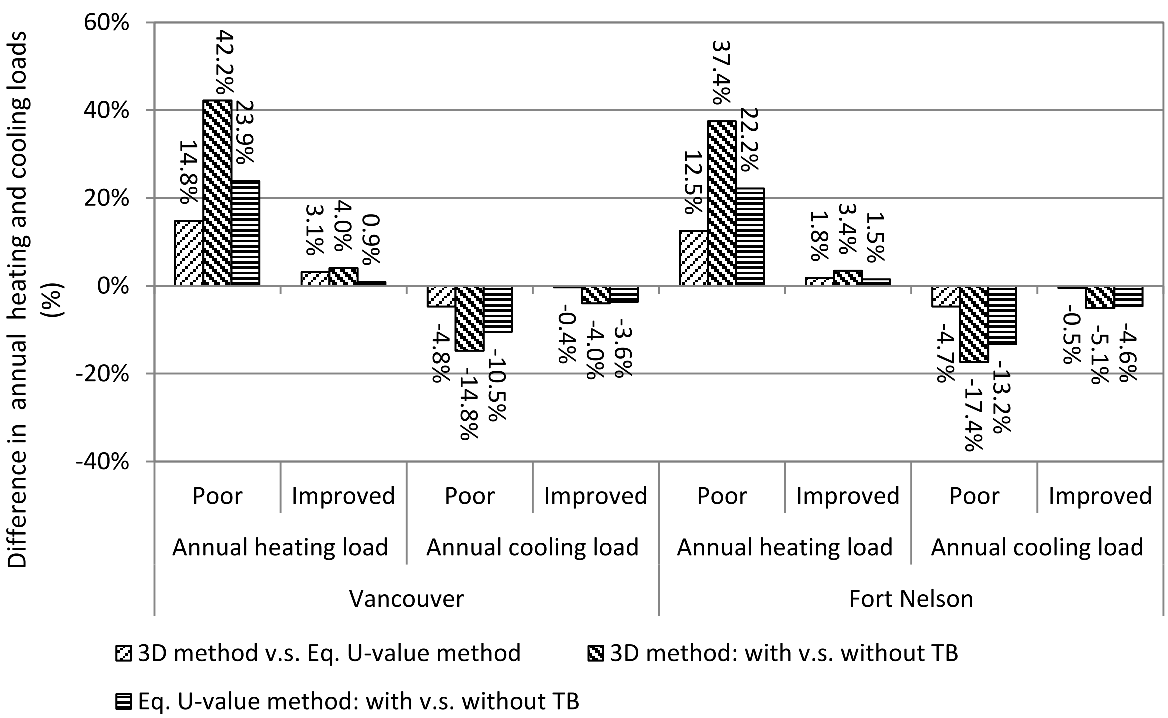


Fig. 3. Percentage difference in annual heating and cooling loads between the two thermal bridge modeling methods.

CONCLUSION

The dynamic effect of thermal bridge junctions on the energy performance of a high-rise residential building is evaluated using WUFI Plus software. The simulation includes modeling the thermal bridges using the 3D dynamic method and the equivalent U-value method. Energy load has been simulated for climate zones 4 and 7 in British Columbia with poor and improved thermal bridges. Simulation results show that the inclusion of thermal bridges increases the annual heating load by 37.4-42.2% for the two cities studied with poor thermal bridges. When the thermal bridges improved, the presence of thermal bridges increases the annual space heating load by 3.4-4.0%. Compared to the dynamic 3D modeling method, the annual heating load is underestimated by 12.5-14.8% using the equivalent U-value method depending on the climatic zones for poor thermal bridges. When the thermal bridges are improved, the difference between the two approaches is decreased to 1.8-3.1%.

In conclusion, the dynamic effect of thermal bridges on the building's energy load increases with using poor construction junctions. For that, the improved connection details in building envelope should be used to eliminate thermal bridges, thus reducing the annual energy load of buildings.

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