**THE USE OF AEROGEL-ENHANCED BLANKET FOR THERMAL BRIDGING CORRECTION IN CONCRETE AND
STEEL BUILDINGS**

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The use of aerogel-enhanced blanket for thermal bridging correction in concrete and steel buildings.

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ABSTRACT

Thermal bridges have been widely proved to significantly impact the building energy performance. This study will use aerogel-enhanced blanket to provide a solution for improving thermal bridges. The common method to include thermal bridges in the whole energy modelling is the equivalent U-value method; this does not take into account the dynamic effect of thermal bridges. Hence this research is focused on the dynamic effect of the thermal bridges before and after the application of aerogel-enhanced blanket in a mid-rise residential building. This study includes: 1) two different building systems: concrete building and steel building 2) three different climate conditions 3) Five different details: balcony to floor, shelf angle location, foundation to wall, wall to floor and wall to roof 4) two different modeling approaches: equivalent U-value method and 3D dynamic method 5) two different thermal bridges: standard and improved details with aerogel-enhanced blanket.

The purpose of this research is to analyze the standard details of thermal bridges and to improve them with the help of aerogel-enhanced blanket. The research aims to determine how effective aerogel-enhanced blanket are for thermal bridging correction and to compare the results between two different building modeling approaches.

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1. BACKGROUND AND SIGNIFICANCE

World's atmospheric temperature is rising at an alarming rate and global warming is a burning issue. The emission of the greenhouse gases today is more than the atmosphere can absorb, resulting on climate changes worldwide. The rise in temperature causes disruption and disaster to the built environment and the ecosystem. Moreover, the significant increase in energy consumption and greenhouse gases from 1990 to 2010 has justified the urgent need for energy reduction (EPA, 2014). The Paris Agreement Central aims to keep a global temperature rise this century below 2 degrees Celsius in the pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius (UNCC, 2018).

With the rapid increase of the global energy demand and evidence of global warming in last decades, energy reduction strategies are being focused. The building sector is responsible for 40% of the total energy consumption and 40% of greenhouse gas emission in most of the developed countries (IEA, 2013). Whereas in Canada residential and commercial building sector consumes about 17 to 32% of the total energy consumption (NECB, 2016). Space conditioning systems, heating, and cooling are among the main responsible for energy consumption, which heavily depends on the climate and the region where the building is located (Santos et al.,2011).

The total energy is consumed by the building in 3 different phases: 1. Manufacturing construction phase– It is the total energy used for the extraction of raw material, processing and manufacturing, and the total construction process. 2. Operating energy phase– It is the energy used for the lifetime. 3. Demolition and potential recycling phase. Among all phases, the operating period of the building differs with different construction system and the local climate. This will govern the total energy consumption and hence is the most significant phase.

A high performance low-energy building is the present-day need. Thermal bridges created by the discontinuity of the thermal insulation significantly affect the overall performance of building envelopes. Thermal bridges are the sources of significant heat loss in the winter and heat gain in the summer. Studies have shown that thermal bridges can increase energy consumption up to 30% in a well-insulated building and can damage the building envelope (Theodosiou & Papadopoulos, 2008). A huge amount of current energy can be saved by the deployment of best available technologies to reduce the thermal bridges in

the buildings. One of the major steps is energy efficient thermal envelope. The improved thermally insulated envelope helps to reduce the heating and cooling load as well as helps to create proper indoor air quality. The thermal envelope design, insulation level, and thermal mass design are the keys for better energy performance. Global energy retrofitting is being the next step for the buildings. (Berardi, 2018)

A study done recently suggests that more effort should be given to design building envelopes with improved connection details (Baba & Ge, 2017). Minimizing thermal bridges in building not only reduces the annual heating and cooling load but also reduce the error in the modeling performance by a commonly used equivalent U-value method (Baba & Ge, 2017). The equivalent U-value method can underestimate the annual heating energy demand by up to 13% for the pour-in-place concrete building with standard connection levels (Baba & Ge, 2017). While the difference between 3D dynamic modeling and equivalent U-value method was reduced to less than 3% when the connections are improved. This suggests that the 3D dynamic method is more accurate as well as improved connection details helps to reduce modeling errors.

The total building energy consumption depends on the selection of insulating materials. Researchers today are investigating to create products with the lowest possible thermal conductivity with high performance building envelopes. Along with the lowest conductivity, it is really important to look at other properties too like fire resistant, mechanical strength, durability, resilience to weather, water resistance, environment-friendly, cost, and human hazard effect. Out of different superior insulating material, the aerogel-enhanced blanket is among the most promising insulating material with thermal conductivity as low as 0.13 W/(mK) (Berardi, 2018). The aerogel-enhanced blanket is used to improve the connection details to achieve a high-performance low energy building.

This research studies the dynamic effect of thermal bridges on building energy performance and to answer the following questions:

1. Is the use of 10mm/20mm aerogel-enhanced blanket sufficient to correct thermal bridges in steel and concrete building?
2. How are thermal bridges calculated from equivalent U-value method differ from the 3D dynamic method?

2. LITERATURE REVIEW

2.1. THERMAL BRIDGE

2.1.1. INTRODUCTION

The best way to reduce heating and cooling building load is to design and construct the energy efficient envelope with high thermal resistance. The energy efficient envelope cannot be achieved only through higher insulation level, but we need to reduce the thermal bridges within the building envelopes. The better envelope is not only a need in new construction but also the old constructions. A significant percentage of the building in Canada needs to be retrofitted as most of the building were built before 1949 (IEA, 2013). The thermal bridges in building envelope not only affect the energy performance but also affect the durability and occupants' thermal comfort (Baba & Ge , 2016).

Thermal bridges are the part of the building envelope where the uniform thermal resistance is slightly changed by full or partial penetration by materials with a different thermal conductivity or material with different thickness or difference between internal and external areas (ISO 10211, 2007). Thermal bridges had impact on the whole building energy use, indoor surface temperature and the human comfort. Some of the material in the assembly is more conductive than the insulating materials which makes a path for the heat flow which are known as thermal bridges. The interfaces and joints like slab, foundation, roof, balcony, cantilever window perimeter are major areas where thermal bridge can occur. Thermal bridge can be avoided by either exterior insulation, interior insulation and blocking the flow path of heat (Vazquez et al.,2015)

Figure 1: Thermal bridge at the external wall corner of original(left) and improved(right) details (Renieri, 2018).

The total heat transfer with in the building envelope occurs by clear filled transmittance and the additional amount of the heat transferred are accounted as linear and point transmittance, commonly known as thermal bridges.

- Clear field transmittance (U_0)-It is the heat flow per unit area through an assembly without any thermal irregularities. Clear field heat flow: $U_0 \cdot A$
- Linear transmittance (Ψ)- Additional heat flow in any detail which can be defined as characteristics length. It is calculated as heat flow per unit length. It is commonly found in the building junctions. Linear Transmittance Heat flow= $\Psi \cdot L$
- Point transmittance (χ)- This is the additional heat flow in any point due to the point thermal bridges. It is the single additional heat flow and usually occurs in penetration with metal fasteners. Point transmittance heat flow= $\chi \cdot$ Number of occurrences.

The proposed U-value or R-values includes all clear field assemblies and linear and point details along all active takeoff values. This is calculated as

$$U_{\text{total}} = U_0 + \frac{\Sigma(\Psi \cdot L) \pm \Sigma(\chi)}{A_{\text{total}}}$$

Where,

U_{total} = total effective thermal transmittance ($\text{W}/\text{m}^2 \text{ K}$)

U_0 = Clear field thermal transmittance ($\text{W}/\text{m}^2 \text{ k}$)

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

Ψ = heat flow from linear thermal bridge

χ =heat flow from point thermal bridge

L = length of linear thermal bridge

2.1.2. BUILDING STANDARDS FOR LIMITING THERMAL BRIDGING

For the proper thermal performance, standard relating to the thermal bridges has been developed worldwide. The European standards were developed since 1995, focusing on the aspects of thermal performance of the building construction including the thermal bridging effect such as ISO 10211-1. For the proper and detailed calculation and simulation the standard was used from ISO 10211:2007 for linear thermal transmittance calculation (ISO 10211, 2007).

- According to National Energy Code of Canada for Buildings (NECB, 2016), thermal bridges can be reduced by providing the continuous insulation in the details like balcony slab, ground floors, roof and wall junction etc. These standards do not specify any temperature distribution calculations. It requires to take into account thermal bridges due to the repetitive structural members such as stud and joists and of ancillary members such as lintels, sills for the calculation of effective thermal resistance of assemblies. However, minor penetration or minor structural members, and major penetration such as balconies with a cross section less than 2% of the penetrated wall area cannot be taken into account for effective thermal resistance.
- ASHRAE 1365-RP – Thermal Performance of Building Envelope Details for Mid- and High-Rise building guidelines include thermal transmittance data focusing on 3D thermal bridges. It contains 40 typical building assembly details with thermal bridges in North America. (ASHRAE 1365-RP, 2011)
- ASHRAE Standard 90.1 has stated the concept of thermal bridging defining the continuous insulation as “Insulation that is uncompressed and continuous across all the structural members without thermal bridges other than fasteners and service openings” (ASHRAE, 2016). It has provided the maximum U-value to the building envelope components for mass, steel, wood frame and for all climatic zones.

2.1.3. STEADY VS DYNAMIC METHOD

With the complex 3D thermal bridges, steady state method of the calculation for building energy demand can be obsolete. For the proper calculation, dynamic analysis is to be done. It is the method of calculating the energy by taking into consideration of the realistic daily condition of the calculation time like daily temperature changes, interior conditions, the rate of natural and artificial ventilation in different seasons and solar gains.

The direct 2D or 3D modeling of thermal bridges in whole building energy simulation increases complexity as well as requires greater computing capacity and time. WUFI Plus, ESP-r programs have the capability to model 2D and 3D thermal bridges on the whole energy building simulation.

2.1.4. METHOD FOR CALCULATING THERMAL BRIDGES

The methods used to calculate the thermal bridge effect in the building is typically Equivalent U-value method and 3D dynamic method.

- Equivalent U-value method

THERM 7.6 is a 2D conduction heat transfer analysis program based on finite element method developed by Lawrence National Laboratory. It calculates the effective U-value for thermal bridges in steady state condition, which is also called as equivalent U-value.

- 3D Dynamic Modeling Method

WUFI Plus, ESP-r programs have the capability to model 2D and 3D thermal bridges on the whole energy building simulation. The direct 2D or 3D modeling of thermal bridges in whole building energy simulation increases complexity as well as requires greater computing capacity and time. WUFI Plus, a whole building Heat, Air and Moisture modeling program allows us to model 3D thermal bridges into the model. It gives the overall performance using dynamic analysis. The building performance is checked with the space heating and cooling energy demand including the thermal bridges in whole building simulation.

Table 1: List of possible thermal bridges and norms.

Areas	Possible thermal bridges	Norms
Opaque building component connections	Floor to floor connection, floor to balcony connection, Wall to roof connection	ISO 10211
Transparent building components, Curtain wall	Mullion- transom, spandrel panel, windows	ISO 10077
Ground contact components	Foundations, conditioned and unconditioned basements	ISO 13370, 10211
Point thermal bridges	Anchors, support, façade dowels	ISO 10211

Even though the material R-value is higher, construction details and penetrations can lower the R-value of the assembly due to thermal bridges. In that case, increasing the thickness of insulation will be

ineffective if the details are not improved. Small changes and addition in the design can change the whole building performance. The continuity of the insulation is one of the ways to mitigate the issues of thermal bridging. Few alteration and careful details can improve the losses from building envelope. The bar chart in figure 2 shows the thermal bridges effects in envelopes with varying thermal resistance. According to the graph, the effect of thermal bridges is higher in a highly insulated building. Improved details can reduce more energy in the well-insulated building.

Figure 2: Thermal performance of wall assembly with different insulation thickness and thermal bridges in a mid-rise MURB building in Edmonton (Morrison Hersfield, 2011)

2.1.5. RESEARCH ON THERMAL BRIDGES

For years, many researchers have performed studies on thermal bridge and its effect in the building, mostly from a modeling perspective. Thermal bridges along with increasing the energy demand, also decrease the interior surface temperature, increasing the risk of condensation and mould growth in the winter. From the studies, in some of building 50% of the total elevation of the building consists of three-dimensional envelope structural details (Kosny & Desjarlais, 1994). A study of representative wall insulation configurations in Greek building was done to know the effect of thermal bridges on energy

demand. The buildings were partially insulated, and the thermal bridges were not taken into account when calculating the energy demand. Considering the thermal bridges in the study, the heating energy increased up to 30% for well insulated residential building adopting high-performance windows and highly insulated walls and roofs (Theodosiou & Papadopoulos, 2008). The study also suggests that the exterior insulation is an appealing solution when it comes to renovating an existing building rather than cavity insulation.

The building energy performance due to the thermal bridges is usually accounted using the equivalent U-value method. It is the method where the adjustment is made to the one-dimensional multilayers envelope to achieve effective u-value of the connection detail with thermal bridges. Mao et al in 1997 suggest that thermal bridges in the building wall not only reduce the thermal resistance of the wall but also changes the dynamic character of the wall. While using this method the material layers of the details are kept the same as the rest of the wall. This does not take in account the inertia effect of thermal bridges.

Ascione et al. (2012) carried out a comparative study between conventional approaches with detailed 2D and 3D simulation model calculating the energy demand in a typical office building in Italy. The result showed a difference of 20% energy demand which suggests the dynamic building simulation should be done for accurate and proper design. WUFI plus software helps in coupling of hygrothermal whole energy building model with a transient 3D thermal bridge allowing a broad range of application (Antretter et al., 2013). This helps to know the effect of dynamic thermal bridge performance on the overall energy demand of the building. The direct 2D and 3D method of building energy simulation are complex as well as need greater computing capacity. Another study by (Karabulut et al., 2016) showed that increasing insulation layers on the exterior helps way better to reduce the thermal bridges. To see the results different configurations were taken and insulating layers were applied to the same geometry.

In 2013, Ge et al. studied the impact of the commercial balcony break on the internal surface temperature, heating and cooling load of the building in Toronto. 2D heat transfer and whole building simulation was evaluated where with the implementation of balcony break, the interior floor surface temperature is greatly improved. Also, improvement of 9-18% was observed in the U-values of the building. Implementing the thermal break allowed 5 to 13% reduction in heating energy consumption and less than 1% reduction in annual cooling energy consumption. It also studied that balcony cross section of 4% of the exterior wall can contribute up to 11% of space heating energy consumption depending on the

thermal performance of building envelope. Also, the performance of the thermal break is higher when the window to wall ratio is reduced, walls are well insulated and with the high-performance building envelope. This shows that there is potential of energy saving if linear thermal bridging is improved.

A sensitivity analysis based on an extensive study of linear thermal transmittance was carried out on many types of thermal bridges. The sensitivity analysis was done not only to properly design structural nodes but also, to appreciate the benefits of a proper design by identifying accurate numerical results (Capozzoli et al., 2013). As linear thermal transmittance affects the energy demand, the performed sensitivity analysis allowed the design variables that have the highest influence on building performance to be identified.

Most of the study were done in 1D whole building energy simulation, where the thermal inertia effect is ignored. Meanwhile, in 2016 Baba & Ge investigated the dynamic effect of balcony slab on the energy performance. For the study they compared the annual space conditioning loads obtained by equivalent U-value method to 3D dynamic modeling of the balcony junction with the WUFI Plus. The implementation of thermal break improves the annual heating load by 7.1-8.8% whereas when the building insulation was increased, the energy saving reaches up to 20.8- 25.7% for 100% balcony slab ratio. From the study, equivalent U-value method underestimates the annual space heating by 8.6%- 15.2% and was reduced to 1.9-11.5% when thermal breaks were implemented. On the contrary, equivalent U-value method overestimates the annual cooling load but is comparatively very less to heating load.

Another similar study on the effect of dynamic modelling of thermal bridges on the energy performance of residential buildings with high thermal mass for cold climate suggests that more effort should be given to designing building envelopes with improved connection details (Baba & Ge, 2017; Ge and Baba 2017). Minimizing thermal bridges in building not only reduces the annual heating and cooling load but also reduce the error in modelling energy performance by a commonly used equivalent U-value method (Baba & Ge, 2017). Similar to the previous result, the equivalent U-value method can underestimate the annual heating energy demand by up to 13% for the pour-in-concrete construction with standard connection levels (Baba & Ge, 2017). While the differences between 3D dynamic modeling and equivalent U-value methods was reduced to less than 3% when the connections are improved. It suggests that the dynamic method of calculating the thermal bridge help to properly calculate the total energy. The study concluded that the dynamic effect is higher with higher thermal mass and a higher amount of thermal bridges.

2.2. AEROGEL-ENHANCED BLANKETS

2.2.1. AEROGEL

Aerogel is low density nanostructured insulating material discovered in the 1930s by Kistler (Kistler, 1932). They are the innovative insulating material with extremely low conductivity ($\sim 0.01-0.02 \text{ W/mK}$) compared to conventional building insulations. Aerogel is the gel whose liquid component is replaced by the air. With a perfect production method, 85-99.8% of the volume of the aerogel consists of air-filled pore sizes between 5 nm to 70 nm (Baetens et al., 2011). These tiny pores are responsible for Knudsen effect resulting in very high thermal resistance. It limits conductive and convective gas transport and its low density provide limited pathways for conduction.

Aerogel in its pure form has very low density and are fragile. This makes aerogel critical for handling and use without fracturing. For this reason, different aerogel enhanced product is produced from mixing with different composite for the application in the various field. Aerogel can be used in the opaque, translucent and transparent application. Aerogels are formed by the sol-gel process in which liquid sol is replaced by the Gel. Aerogel can be prepared from a different material but the most common is silica aerogel because of its comparatively easy and cheaper production cost (Najjar, 2012). Despite superior thermal insulating properties, aerogel is slowly finding their application in the building industry due to availability and the cost. The present research efforts are on the ways of reducing the time and cost of the manufacturing process of the aerogel. The aerogel-enhanced products are used for building with space constraints.

Table 2: Physical properties of silica aerogels (Berardi, 2018)

Properties	Ranges
High porosity	85-99.9%
Low density	3 to 350kg/m ³
Thermal Conductivity	0.01- 0.02 W/mK
High specific surface area	600-1000 m ² /g
Tensile Strength	16 KPa
Compressive strength	300 KPa

In porous material like aerogel, the heat transfer mechanism is contributed by six methods: solid state thermal conductivity, gas state thermal conductivity, radiation infrared thermal conductivity, gas state convection thermal conductivity, leakage thermal conductivity, and second order thermal conductivity. All the modes are minimized by the aerogel's structural structure.

1. Conduction through solid material. Aerogel has very less solid silica and most of them are dead ends which leads in low thermal conductivity.
2. Conduction through the gas present in between the pores. The conductivity is directly related to the size of the pore. Aerogel is a Nano porous structure so has negligible heat transfer.
3. Convective transport by air and vapor in the pore medium can be neglected due to its small pore size as it prevents Brownian motion of gas.
4. Radiation from solid surfaces through the pore fluid can also be neglected as the materials are dry, less permeable and have no holes.
5. Radiative transport by the solid network. Aerogels due to its low bulk density and addition of opacifier, the energy is absorbed or scattered reducing the heat transfer.
6. Second order thermal conductivity is directly related to second order discussed above and is normally negligible.

2.2.2. AEROGEL BASED PRODUCTS FOR BUILDING APPLICATION

The main building products for building insulations are: aerogel mortar, aerogel plaster, aerogel enhanced blanket, aerogel concrete. Meanwhile, thanks to the translucent characteristics of the aerogels, their introduction in glazing systems has been proposed both using monolithic aerogels and granular ones for enhancing high thermal resistance and still high visible transmittance (Gao et al., 2014; Berardi, 2015).

2.2.3. AEROGEL-ENHANCED BLANKETS

Aerogel-enhanced blanket is the super insulating materials developed from the silica aerogel and reinforced fibre. As shown in table 2, pure silica aerogels have higher compressive strength whereas low mechanical strength and stability. To strengthen the tensile property of aerogel, it is interwoven with the fibrous material. When the fibres or fibrous matrix are added to the pre-gel mixture which contains the gel precursors, the resulting dried composite is an aerogel blanket (Aegerter et al., 2011; Baetens et al., 2011). It is obtained by wet gel impregnation and supercritical CO₂ drying.

Figure 4: Aspen aerogel blanket.

Source: <http://www.buyaerogel.com/product/spaceloft/>

Figure 3: Spaceloft aerogel blanket for buildings

(Source: <https://www.aerogel.com/markets/building-and-construction/>)

Aerogel-enhanced blankets are mechanically strengthened, flexible and highly porous material with very low thermal conductivity. Aerogel-enhanced blankets because of its unique nature can be used in interior as well as exterior applications. Aerogel-enhanced blankets have high fire resistance making it possible for the interior application for the retrofit. Its hydrophobic properties help it for the exterior insulation. The aerogel-enhanced blanket is considered promising material not only in building sectors but also automobiles, aircraft, industrial, mechanical systems, and clothing items. Aerogel-enhanced blankets composed of synthetic amorphous silica dioxide have been proposed in retrofitting projects or whenever space and weight constraints exists (Cuce & Cuce, 2016, Galliano et al., 2016). It is also found to be more advantageous in building retrofits for space saving since they help achieving high resistance in thin layers (Koebel et al., 2012).

2.2.4. AEROGEL-ENHANCED BLANKET MARKET

The aerogel market is increasing by 10 % annually with USD 307.5 in 2014, USD427 million in 2016 and expected to reach USD 3.29 billion by 2025 (GVR, 2018). The aerogel market is expected to expand due to the increase of robust building and construction as well as its application in various industries. Aerogel manufactures are trying to deal with the challenging aspects: the cost and minimize fabrication dust. The graph in table 3 shows that the thickness and the material cost to achieve $U=0.2W/2K$. To achieve the same U-value, aerogel require less than half of the thickness of the conventional insulating material. But

the cost of aerogel blanket seems to be 20 times higher than conventional insulation. The aerogel-enhanced blanket is made cost-effective by immersing common fibre glass in aerogel precursor chemicals in the gel form and is vacuum oven dried for 24 hours (Berardi, 2017).

The Manufactures are now producing the aerogel blanket commercially. The leading manufactures are Aspen Aerogel, Inc, Cabot Corporation holding a majority share of global market. (GVR, 2018). The table 3 shows the main properties of different aerogel-enhanced blankets available on the market.

Table 3: Main properties of different aerogel-enhanced blankets available on the market. (Berardi, 2018)

Provider	Commercial name	Fiber composition	Density (kg/m ³)	Conductivity (W/mK)
Aspen Aerogel	Cryogel X 201	Polyester/fiber glass	~130	0.014
	Cryogel Z	PET/fibrous glass	~160	0.014
	Pryogel HPS	Fiberglass	~200	0.014
	Pryogel XTE	Fiberglass	~200	0.014
	Pryogel XTF	Fiberglass	~200	0.014
	Spaceloft	Polyester/ fiberglass	~151	0.015
Cabot Aerogel	Thermal Wrap	Polystyrene and PET	~70	0.023
Dow Corning	Dow Corning HPI 1000	Silicon		0.015
Joda	Silica aerogel fiberglass blanket, SACB-0-x	Fiber glass	<300	0.016
	Silica aerogel ceramic fiber blanket, SACTT-	Ceramic fiber	<301	0.016

2.2.5. PROPERTIES OF AEROGEL-ENHANCED BLANKET

Aerogel-enhanced blanket is best known as super-insulating material after VIPS. Figure 5 shows the comparison of the thickness of the insulating material required to obtain an RSI of 5.67. The thickness of aerogel-enhanced blanket is comparatively low than other insulation material available in market except

for vacuum panel. Even with the smaller thickness, it can provide higher resistance. The thermal conductivity of aerogel-enhanced blanket is found in the range of 0.014 to 0.016W/mK. The aerogel blankets are fire resistance and hydrophobic which makes it possible to use in the outdoor application also.

Figure 5: Thickness of the insulating material to achieve RSI -5.6 (Source: <https://hub.globalccsinstitute.com/publications/zero-carbon-australia-buildings-plan/2-improving-thermal-performance-building-envel>)

A study was done in two different aerogel-enhanced blankets for thermal conductivity in a humid condition in transient and steady-state regimens in 2016 by Hosseini et.al. Moisture in both samples was measured as a function of temperature and relative humidity. The thermal conductivity can increase up to 15% with the change of ambient relative humidity from 0 to 90% at 25 degrees. On the contrary, the study done by Norasti and Berardi on the aging of aerogel blankets for elevated temperature and freeze thaw and weathering and humidity driven aging reveal that there is no significant impact (1%) on aerogel blankets under elevated temperature and freeze-thaw cycles (Berardi & Nosrati, 2018). However, the thermal conductivity increases by 10% to 8.4% due to weathering and humidity driven ageing. The result suggests for proper hygrothermal analysis for long term performance of the aerogel-enhanced blanket. The moisture needs to be avoided for the drastic change in the R-value of the aerogel insulation.

The aerogel blanket studied under the compressive mechanical loading to see the effect on the thermal conductivity and mechanical deformation shows that the aerogel blanket has very less amount of changes (Hoseini et al., 2016). The maximum decrease of the thickness was about 20% for 8mm thermal wrap blanket whereas 10% for a 10mm Cryogen sample. Though greater changes on thickness, the thermal conductivity decreases were less than 5%.

2.2.6. RESEARCH ON AEROGEL-ENHANCED BLANKET

Aerogel-enhanced blankets are innovative material for thermal bridging correction in the building sector. Studies state that aerogel enhanced blanket has already been used commercially for the thermal bridging correction in wood and steel frame building. Thermoblok aerogel insulation strips are used in interior and the exterior face of a wall stud, header, window frames, door frames, and floor joist to break thermal bridges. Aerogel strip of width 25-30mm was used (Thermablok, 2018). A study shows improvement of R-value of wall assembly up to 42% with the use of aerogel insulation strip on the warm side of the 2 x4 metal stud wall (Thermablok, 2018). Few case studies have been done regarding aerogel-enhanced blanket as interior and exterior insulation for new and retrofit buildings for roof insulation, floor and balcony insulation, thermal bridge corrections (Aspen Aerogels, 2018)

A recent study done by Berardi on the retrofit of an educational building in Toronto used aerogel-enhanced products. Aerogel-enhanced blanket was used below the windows and its effectiveness was studied by annual saving and cost (Berardi, 2017). It shows a payback period of ~17 years and also states that the results are sensitive to the type of building and its location. Another study by (Beaten et al., 2016) used Spaceloft aerogel-enhanced blanket of the thickness of 10 mm. A thermographic image of retrofitted timber wall with a thin layer of aerogel enhanced blanket in stud shows that it helps to reduce the thermal bridges in wood frame or steel frame envelopes.

Cuce & Cuce conducted experimental and statistical research on 2016 to study the impact of internal aerogel retrofitting on thermal bridges of the residential building. 20mm thick aerogel blanket was implemented internally and heat flux was measured for pre and post-retrofit. The results reveal that the heat loss from the non-insulated wall after internal retrofit increases. This study suggests that the thermal bridging effects should be studied properly for successful internal retrofit. Shukla et al. (2014) studied cost-effectiveness of aerogel enhanced blankets for interior wall retrofit. It shows that aerogel-enhanced blanket saves 18-23% of the total installation cost compared to the conventional method. Interior wall

retrofit with 10mm of aerogel-enhanced blanket was proved to be advantageous in real state saving. The aerogel-enhanced blanket has the advantage of saving the space with the superior insulation because of its high thermal resistance even in thin layers (Galliano et al.,2016).

Improving the building envelope resistance through conventional insulation requires space which can potentially impact on the architectural integrity or might reduce the living space for the tenants. Aerogel-enhanced blanket has also benefit in Heritage Sector as aerogel-enhanced blanket provide best performance in minimum thickness. Space loft aerogel blanket was installed on Church roof in Northern Ireland as the best performance was required on minimum space due to coping restriction on the roof. (Aspen Aerogels, 2018). Space loft aerogel-enhanced blanket insulation strips are applied to the exterior framing of the residential new construction increase the thermal resistance by 15 %.

A facadectomy technique as shown in fig 6 for exterior wall application for MA Housing Authority where the brick is replaced with the insulation layer and the stucco/ EIFS system seems one of the ways for retrofitting the existing building using aerogel (Aerogels, 2011). R-5 wall is improved to R-15 with the same space after the facadectomy technology.

Figure 6 Facadectomy technique applied for the retrofit of MA Housing Authority building. Left: standard, Right: improved

3. METHODOLOGY

To study the improvement of energy performance of the thermal bridge through correction with aerogel-enhanced blankets, the details are simulated for their annual heating and cooling energy demand. Two different modelling approach issued for the study: 1) Equivalent U-value method and 2) 3D dynamic method. This section presents the details of the building with thermal bridges, the case study building and the boundary conditions for the simulations. This research investigates the energy performance in different construction systems and the improvement that can be achieved using aerogel-enhanced blanket in the building. The payback period calculation is done to investigate if the aerogel-enhanced blanket is beneficial.

Figure 7: Simulation scenario for the research

3.1. TYPICAL THERMAL BRIDGE JUNCTIONS

To assess the thermal bridge and their effects, two different construction types, concrete building and steel building are considered. The typical thermal bridges in each building included are 1) Floor to wall junction; 2) Balcony to wall junction; 3) Shelf angle detail; 4) Foundation to wall; 5) Wall to roof; and 6) Sill and lintel detail. The 10mm or 20 mm Aspen aerogel blanket was selected for carrying out the investigation of correction of thermal bridges.

3.1.1. CONCRETE BUILDING DETAILS

In concrete building, concrete is comparatively more conductive than other elements in the assembly. So, there are thermal bridges on transition areas. The details are improved by the aerogel-enhanced blanket at the location where the insulation is insufficient or have penetration with a conductive material.

DETAILS

Connections 1 to 5 of figure 8 represents the details of the junction that are likely to have thermal bridges in the concrete buildings. The detail contains wall and balcony detail, window detail, wall and floor detail, shelf angle detail and wall and foundation detail. The detail at left and right is the standard detail and improved detail respectively.

Connection 1 :Wall and floor

Standard

Improved

Connection 2 :Window lintel and sill

Standard

Improved

Connection 3: Shelf angle detail

Standard

Improved

Connection 4 : Foundation and Wall connection

Standard

Improved

Connection 5 :Wall and balcony connection

Figure 8: Connection details of concrete building; standard details (left) and improved details (right)

3.1.2. STEEL BUILDING DETAILS

Steel is a highly conductive material compared to other materials in the assembly. The structure and the details are very prone to thermal bridges in this construction system. The standard details have no any

thermal resistive materials in steel to steel connection creating a path of heat flow. Therefore, in the improved design detail, the aerogel- enhanced blanket has been used in the junctions as shown in fig. 9.

Connection 1 :Wall and floor detail

Connection 2 :Wall and balcony detail

Connection 3::Wall and roof detail

Connection 4 :Window lintel detail

Figure 9: Connection details of the steel building; standard details (left) improved details (right)

3.2. CASE STUDY BUILDING

The case building for this study is a mid-rise residential building in Canada. The building is 2 storey, 31.9 m long by 17.78 m wide by 6 m tall with approximately 1114 m² gross floor area. The building is designed as per the baseline model with the different building envelope and climatic condition. Window to wall ratio of 40% is used for the study. The building was first modelled in the SketchUp as shown in figure 10, and then imported into WUFI Plus. The figure 10 is the typical floor plan. The connection details in each of the buildings are shown in the figure 8 and 9.

Figure 10: Typical floor plan of the base building

The building is divided into 5 thermal zone: north, south, east, west and the middle zone as shown in figure 11. Simulations are done by two different method i.e. WUFI Plus which is a direct 3D dynamic modelling method adding 3D thermal bridges and equivalent U-value method giving linear thermal transmittance value in thermal model.

Figure 11: Sketchup file of 2 storied base building with window to wall ratio of 40%.

3.3. SIMULATION SCENARIO

The model with the standard details was simulated to see the energy consumption of a typical building with thermal bridge details. The details were then improved by using the aerogel-enhanced blanket to see how much energy can be saved using aerogel enhanced blanket to correct thermal bridges. The base building with no any thermal bridge was simulated in different climate zones to create a baseline for the simulation and to find the percentage improvement in energy demand.

3.3.1. CLIMATIC CONDITIONS

To study the dynamic behavior of the thermal bridges, three different climates are chosen for whole building energy simulation. The locations are selected from different climatic zone to compare the effect of thermal bridges in different climate. The table 4 shows the minimum temperature in winter, maximum temperature in the summer and mean temperature of the selected location from WUFI Plus program which is based on Oak Ridge National Laboratory, USA. The figure 12 shows the temperature curve of the Toronto in steady state as well as dynamic state.

Table 4: Maximum, mean and minimum temperature for three climate zones

Location	Climate zone	Maximum temperature °C	Mean temperature °C	Minimum temperature °C
Vancouver	4	27.2	9.06	-11.1
Toronto	6	32.8	6.7	-23.3
Calgary	7	30.6	2.54	-36.7

Figure 12: Exterior temperature profile for Toronto city climate in WUFI Plus.

For the ground floor and the foundation, optional climate was defined to model the building in the WUFI plus. The ground condition is defined as per the Canadian Climate Normals 1971-2000 Station Data. For the different climatic zone, different sine wave with a mean value and an amplitude temperature are assigned. Table 5 represents the temperature profile of the ground which is 50cm below the grade for each location (Government of Canada, 2018)

Table 5: Optional climate for ground temperature

Location	Mean Value	Amplitude
Vancouver	12	6
Toronto	11	7
Calgary	10	8

3.3.2. MODELLING APPROACHES

- Equivalent U-value method

THERM, 2D conduction heat transfer program is used to calculate the thermal transmittance value using steady state conditions. The subsurface are created and 1D building envelope components are added in whole building energy simulation. The overall U-value obtained from THERM is provided to calculate the equivalent U-value. Thickness of other two layers and physical properties are kept the same in 1D multi-layer structure. The dimensions are taken from the interior wall. First the junction was drafted on AutoCAD which is then imported to THERM converting into .dxf file which is more accurate as well as easy to draw the details.

Linear thermal transmittance or psi value is the heat loss associated with non-repeated thermal bridge. Linear thermal transmittance can have a negative or positive value. The negative value indicates that the thermal resistance of the building envelope is better than the adjacent assembly whereas positive value represents that the junction has thermal bridges and is reducing the thermal resistance of the envelope system. The less the Psi value, the better is the thermal resistance of the junction.

The U-values of all the junction are calculated in the THERM program with the temperature difference of 39 °C with the exterior boundary condition of -18°C and interior boundary condition of 21°C.

- Direct 3D dynamic modelling method.

WUFI Plus is the program to draw 3D thermal bridges directly in the whole building energy simulation under realistic conditions. It provides access to dynamic hygrothermal building simulation. Antretter et al. (2013) validated WUFI plus program for modeling the 3D thermal bridges under steady state condition to DIN EN 1021 standard (ISO 10211, 2007).

At first, all the thermal bridges to be modelled are listed in the 3D object, as shown in box 1 in fig. 13 for concrete building and steel building. The base building is imported in WUFI Plus, as shown in box 2. After that, the thermal bridges are modelled determining the dimensions on X, Y and Z axis as shown in box 3 in figure 13.

Figure 11: Screenshot of the 3D thermal bridges to 3D object list

The materials for each detail as shown in box 4 are selected as per the junction details. Finally, the boundary conditions as stated 5 are defined for each detail which will help to link the thermal bridges to the zones in base building for whole building simulation. Finally, a 3D thermal bridge with all the materials and boundary condition is modelled as shown in box 6. As the thermal bridges is already accounted from the 3D object, the total volume is the whole building volume excluding the portion of the walls that have been modelled in 3D object. This will help to avoid double counting of the 3D thermal bridge.

Figure 12: 3D models of the thermal bridges junction with boundary condition Left: Balcony detail Right: Foundation details.

The temperature distribution can be observed during the calculation in all axes as shown in figure 15, but this has no effect on the results (Antretter, et al., 2017). The temperature at the monitor point can only be analysed after the calculation.

Figure 13: Temperature difference films that can be observed during the calculation.

3.3.3. SIMULATION INPUTS

- Use, Occupancy and lighting

The analysed building was considered a residential building, where the use, occupancy and lighting was taken from the passive house residential dwelling standard per m². Each zone was assigned with the same values in all the simulation carried out to see the changes achieved only through the thermal bridges. The clothing is taken as 0.7clo and air velocity as 0.1 m/s.

Table 6: List of Internal loads/ Occupancy

Reference	Reference unit	Heat convective (W)	Heat radiant (W)	Moisture (g/h)	CO ₂ (g/h)	Human activity (met)
PHPP	Area	1.58	0.53	2	1.7	1.2

- Materials and assembly

The materials that were selected for the study in WUFI Plus are listed in the table 7, where the thickness of the aerogel-enhanced blanket is 0.01/0.02 in the building detail application as shown in the connection details in fig 8 and 9.

Table 7: List of the materials used in the building assembly, properties and thickness

Material	Conductivity λ (W/mK)	Density ρ (kg/m ³)	Heat capacity C(J/kg. K)	Thickness (m)
Brick	0.6	1900	850	0.114
Air gap 25 mm	0.155	1.3	1000	0.025
Extruded Polystyrene	0.025	28.6	1470	0.081
Insulation				
Oriented Strand Board	0.13	595	1400	0.008
Concrete (w/c =0.5)	1.6	2300	850	0.152
Gypsum Board	0.2	850	850	0.012
Aspen aerogel	0.014	146	1000	0.01/0.02

The overall U-value of the 1D building envelope components are listed in the table.

Table 8: Overall thermal transmittance of building components (W/m^2K)

Building Envelope components	Concrete ($W/m^2 \cdot K$)	Steel ($W/m^2 \cdot K$)
External walls	0.25	0.23
Foundation	0.25	0.25
Roof Slab	0.23	0.23
Interior partition	0.36	0.36

- Temperature, humidity

According to the ASHRAE 90.1 Baseline modelling assumption, the heating setpoint is 21°C with a night setback temperature of 18°C (22:00- 6.00) whereas the cooling setback temperature is set to 25°C with a night setback temperature of 27°C (22:00- 6.00). The relative humidity is kept to 40%.

- Ventilation

The natural ventilation was kept to 0(1/hr) whereas the mechanical ventilation was kept to (0.2)1/hr on the weekdays whereas 0.31 (1/hr) on the weekends.

- HVAC

A central HVAC system is used for heating and cooling of the building and a dedicated air conditioning for dehumidification and humidification in the building.

3.3.4. ENERGY SAVINGS AND COMPARATIVE STUDY

Simulations results are analysed on the basis of annual heating and cooling load. The results are compared and analysed for each case from the results obtained. A comparison between 3D dynamic method and equivalent U-value methods were compared for both steel and concrete building. A percentage difference was calculated for the study where the base case is the building with no thermal bridges. Also, the effect of climatic condition on energy demand was analysed.

4. RESULTS

4.1. EQUIVALENT U-VALUE METHOD

4.1.1. Psi VALUE BY THERM

Tables 9 and 10 show the Psi-value/ ψ -value of the different junctions determined from THERM. The standard ψ -value are the thermal transmittance value of original details whereas the improved ψ -value are thermal transmittance value after improving details with aerogel-enhanced blanket. The drawings in the Appendix–1 show the heat flux of standard and improved details obtained from THERM simulations. Heat flux shows the improvement after the use of aerogel-enhanced blankets and gives an idea of areas which still need to be improved to maintain a comfortable temperature in the interior. Appendix -2 shows linear thermal transmittance calculation.

Table 9: Overall linear thermal transmittance from THERM of concrete building thermal bridge details.

Building Envelope connection details	ψ-value Standard (W/mK)	ψ-value Improved (W/mK)
Balcony details	0.43	0.05
Wall and floor detail	0.20	0.08
Foundation detail	0.57	0.23
Shelf angle detail	0.65	0.12
Window details	0.33	0.15

Table 10: Overall linear thermal transmittance from THERM of steel building thermal bridge details.

Building Envelope connection details	ψ-value Standard (W/mK)	ψ-value Improved (W/mK)
Balcony details	0.85	0.22
Wall and floor detail	0.81	0.29
Window detail	0.55	0.09
Roof detail	1.27	0.14

The ψ -value of standard details are comparatively higher than the standard details. In details of concrete building, shelf angle has higher ψ -value of 0.65 (W/mK) which is improved to 0.12(W/mK). The improvement was up to 0.05(W/mK) in concrete building in balcony detail. Whereas, the roof details ψ -value was improved from 1.27(W/mK) to 0.14(W/mK). The reduction in linear transmittance value are different for details in the buildings. The standard window detail in the steel building is 0.55(W/mK) and with aerogel enhanced blanket is changed to 0.09(W/mK).

4.1.2. ANNUAL SPACE HEATING AND COOLING DEMAND FOR CONCRETE BUILDING

Table 11 shows the total annual heating and cooling loads for concrete building in three different climatic zones; a) Vancouver; b) Toronto; and c) Calgary using the equivalent U-value method. The annual heating demand before using the aerogel enhanced blanket was 163MWh, 183MWh and 233MWh for Vancouver, Toronto and Calgary respectively. But after the details are improved with aerogel-enhanced blanket the heating load decreased to 158MWh, 176MWh and 225MWh respectively. For concrete building, up to 8MWh improvement is observed in the heating load whereas the cooling load can be increased up to 1 MWh which is comparatively much less than the improvement in heating load. The cooling load is only 14% of the heating load. Calgary has got high heating energy saving whereas the increase of cooling energy is high in Toronto.

Table 11: Heating and cooling energy demand of concrete building obtained by using equivalent U-value method

Equivalent U-value method	Vancouver	Toronto	Calgary	Vancouver	Toronto	Calgary
	Heating load			Cooling load		
Original (KWh*10³)	163.37	183.04	233.24	20.36	23.18	17.85
Improved (KWh* 10³)	158.04	176.15	225.13	20.69	24.25	17.99
Without thermal bridges (KWh* 10³)	150.30	167.80	212.85	20.69	24.25	17.99

Improvement in (KWh*10³)	5.33	6.99	8.11	-0.33	-1.07	-0.14
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4.1.3. ANNUAL SPACE HEATING AND COOLING DEMAND FOR STEEL BUILDING

As for the steel construction, Table 12 shows the total annual heating and cooling loads in three different climatic zones; a) Vancouver; b) Toronto; and c) Calgary using the equivalent U-value method. The annual heating demand before using the aerogel enhanced blanket was 168MWh, 198MWh and 244MWh for Vancouver, Toronto and Calgary respectively. With the use of aerogel-enhanced blanket the heating load decreased to 162MWh, 188MWh and 233MWh respectively. We can observe the energy saving up to 11MWh in Calgary. On the contrary, we can see that the cooling load gets higher with the improved details but it only 1.9 MWh which is very less compared to the heating load. For steel building, 4-6 % of improvement is observed in the heating load whereas the cooling load can be increased by 1-8%. Calgary has got highest heating energy saving whereas the increase of cooling energy is high in Toronto.

Table 12: Heating and cooling energy demand of steel building obtained by using equivalent U-value method

Equivalent U-value method	Vancouver	Toronto	Calgary	Vancouver	Toronto	Calgary
	Heating load			Cooling load		
Original (kWh*10³)	168.37	198.04	244.24	21.72	23.15	18.98
Improved (kWh*10³)	162.44	188.16	233.25	22.08	24.38	20.97
Without thermal bridges (kWh*10³)	148.30	174.64	214.41	24.52	26.85	22.92
Improvement in (KWh*10³)	5.93	9.88	10.99	-0.36	-1.23	-1.99

4.2. 3D DYNAMIC METHOD

5.2.1. ANNUAL SPACE HEATING AND COOLING DEMAND OF CONCRETE BUILDING

Table 13 shows the total annual heating and cooling load required for concrete building calculated by 3D dynamic method. The heating load for the building with original details are 184.83 MWh, 219.74 MWh and 269.77 for climatic zones Vancouver, Toronto and Calgary respectively. The heating energy demands are higher from milder to colder climate. In the simulation after the use of aerogel enhanced blanket, the annual heating was reduced by 9.14MWh, 13.63MWh and 15.67 MWh respectively. While the annual cooling load are increased by 0.53 MWh which can be neglected compared to the saving in annual heating load. The highest energy savings were observed in Calgary (15.67MWh).

Table 13: Heating and cooling energy demand of concrete building obtained by using 3D dynamic method

3D dynamic method	Vancouver	Toronto	Calgary	Vancouver	Toronto	Calgary
	Heating load			Cooling load		
Original (kWh*10³)	184.83	219.74	269.77	21.32	23.52	17.16
Improved (kWh*10³)	175.69	206.11	254.1	21.58	24.05	17.6
Without thermal bridges (kWh*10³)	150.30	167.80	212.85	20.7	24.54	17.90
Improvement in (kWh*10³)	9.14	13.63	15.67	-0.26	-0.53	-0.44

4.2.1. ANNUAL SPACE HEATING AND COOLING DEMAND OF STEEL BUILDING

The total annual heating and cooling load calculated using 3D dynamic method for standard, improved and no thermal bridges are shown in table 14. The presence of thermal bridges increased heating load on the building in all climatic zones. The annual heating load due to aerogel-enhanced blanket is reduced by

16-31 MWh, whereas the cooling load increased by 1- 3 MWh. Toronto has the high energy saving of 27.38 MWh, which is almost equal to the saving for Calgary (31.37 MWh). And the increase in cooling load is higher in Calgary (3.3MWh) followed by Toronto (2.97 MWh). Milder climate (Vancouver has low heating energy saving as well as less increase in cooling load.

Table 14 :Heating and cooling energy demand of steel building obtained by using 3D dynamic method and its percentage improvement.

3D dynamic method	Vancouver	Toronto	Calgary	Vancouver	Toronto	Calgary
	Heating load			Cooling load		
Original (kWh*10³)	190.94	236.59	290.71	19.9	24.84	18.19
Improved (kWh*10³)	174.5	208.97	259.34	21.86	27.81	22.02
Without thermal bridges (kWh*10³)	148.30	174.64	214.41	24.52	26.85	22.92
Improvement in (kWh*10³)	16.44	27.38	31.37	-1.96	-2.97	-3.83

4.2.2. RESULTS OF HEATING AND COOLING LOAD AT DIFFERENT ORIENTATION OF BUILDING

The study was done to see the change in annual heating and cooling load in the building due to the different orientation. In the above-simulated building, thermal bridges were only considered for one of the façades for the concrete construction for Toronto climate. The table 15 shows that about 3MWh difference in annual heating load between thermal bridge in different orientation. Whereas the annual cooling load variation seems higher up to 2.5 MWh using the 3D dynamic method.

Table 15: Annual heating and cooling load with thermal bridges at the different orientation.

	Annual heating load (kWh*10 ³)	Annual cooling load (kWh*10 ³)
East	216.10	23.66
West	216.19	23.75
North	219.22	23.51
South	217.35	21.8
No thermal bridge	167.8	24.42

4.3. 3D DYNAMIC METHOD VS EQUIVALENT U-VALUE METHOD

For more clear understanding, all the simulations output is analysed on the percentage difference. The space heating and cooling energy demand obtained without modelling the thermal bridges into the building were used as the reference to calculate the percentage difference. The table 16 and 17 show the percentage differences calculated compared to the energy demand of building with no thermal bridges for concrete and steel building. The percentage difference of annual heating and cooling load between 3D method vs equivalent U-value method, equivalent U-value method vs. building with no thermal bridges, and 3D dynamic method vs. building with no thermal bridges were calculated. The energy difference between buildings with and without thermal bridges shows the effect of thermal bridges. And the difference between the 3D dynamic and equivalent U-value method helps to compare two modelling approaches used.

Table 16: Percentage difference between standard and improved using equivalent U-value method and 3D dynamic method for concrete building.

	Heating Load						Cooling Load					
	Vancouver		Toronto		Calgary		Vancouver		Toronto		Calgary	
	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved
3D vs Equ. U	14.28	11.74	21.87	9.00	17.16	13.61	-4.64	-4.30	-1.39	-0.81	-3.85	-2.18
3D vs without TB	22.97	16.89	30.95	22.83	26.74	19.38	-3.00	-4.25	-4.16	-0.02	-4.13	-1.68
Equ. U vs without TB	8.70	5.15	9.08	4.98	9.58	5.77	-1.64	-0.05	-5.54	-1.18	-4.16	0.50
All the units are in percentage												

Table 17: Percentage difference between standard and improved using equivalent U-value method and 3D dynamic method for steel building.

	Heating Load												Cooling load											
	Vancouver				Toronto				Calgary				Vancouver				Toronto				Calgary			
	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved	Standard	Improved				
3D vs Equ. U	15.219	8.132	22.074	9.626	21.673	12.168	-0.897	-7.423	-6.294	-12.775	-3.447	-4.581												
3D vs without TB	28.753	17.667	35.473	17.367	35.586	20.955	-10.842	-18.842	-7.486	-3.500	-20.637	-3.927												
Equ. U vs without TB	13.533	9.535	13.399	7.742	13.913	8.787	-11.419	-13.780	-9.199	-13.780	-13.780	-8.508												
All the units are in percentage																								

5. DISCUSSION

The discussion is organized on the basis of the research question expressed in section 1.

5.1. IS THE USE OF 10MM/20MM AEROGEL-ENHANCED BLANKET BENEFICIAL TO CORRECT THERMAL BRIDGES IN STEEL AND CONCRETE BUILDING?

This section will discuss the improvement observed with the use of aerogel-enhanced blanket using both equivalent U-value and 3D dynamic method. THERM results were the preliminary step to equivalent U-value method. The annual heating and cooling load obtained from WUFI Plus helped to accomplish the research objective.

5.1.1. RESULTS FROM THERM

In term of the 2D heat transfer method used to analyse the details, it can be clearly observed that the standard ψ -value are higher than the improved ψ -value. In general, improvement can be achieved if the ψ -value get close to 0 W/mK or less. Since ψ -value is the additional heat flow from the junction, the higher ψ -value shows that there is more energy loss from the thermal bridges and has higher opportunities to improve them. And the improved ψ -value is less as the use of aerogel-enhanced blanket acts as a thermal break. The varying reduction of ψ -value depends on the thickness and strategies of aerogel-enhanced blanket used. The thermal transmittance value shown in table 10 and 11 corresponds to the heat flux of the details in Appendix 1. The use of aerogel-enhanced blanket not only helps to reduce the heat transfer but also helps to provide a comfortable interior surface temperature. For this reason, the use of aerogel-enhanced blanket as thermal break helps to reduce overall U-value.

Since the improved ψ -value are still higher than zero, it tells us that there are still more opportunities for improving the details. The thickness of aerogel-enhanced blanket used to correct the thermal bridges in this research is 10mm and 20mm, which can be further increased to achieve lower ψ -value. Also, from the figures in Appendix 1, there are few areas where the aerogel-enhanced blankets can be applied to further reduce the ψ -value. We should also consider that the changes cannot compromise the structural performance of the building. The aerogel-enhanced blanket has allowed insulation in air gap but still, it is limited to the thickness of airgap that is available. For the aerogel-enhanced blanket on the exterior surface, moisture management should also be considered.

5.1.2. IMPROVEMENT IN HEATING ENERGY.

It was observed that the annual heating and cooling energy increase with the thermal bridges in the building. From the study, in concrete building up to 32% increment whereas in steel building up to 35% increment was observed when thermal bridges were accounted to the model. This is as expected because the thermal bridges increase the amount of heat loss, increasing the energy demand of the building as discussed in the literature (Theodosiou, 2008; Theodosiou et.al.,2015). The energy demand for the same building was found to vary in the different climatic zone. This is due to the fact that the heat loss is directly related to the temperature difference between the exterior and interior temperature. Due to lower exterior temperature, Calgary has the high heat loss compared to Vancouver in all the cases. The heating energy is low for milder climate whereas as it goes up in colder climates.

The use of aerogel-enhanced blanket in steel and concrete building reduce the significant amount of space heating energy. The graph in figure 14 and 15 shows the improvement that can be achieved annually per m^2 of the conditioned area in three different climatic conditions for concrete and steel building respectively. The energy demand calculated from equivalent U-value method for concrete building as well as steel building are comparatively lower than the 3D dynamic method. For example, the annual heating energy saving of 5 KWhr/ m^2 is observed for Vancouver using the equivalent U-value method whereas 8 KWhr/ m^2 when calculated from 3D dynamic method.

Figure 14: Energy saving achieved by improving details in concrete building using two different modelling approach

Figure 15: Energy Saving achieved by improving details in steel building using two different modelling approach

Compared to the energy saving in different climates, Toronto savings seems to be higher (27.38 KWh/m²), almost closer to the Calgary (28.6 KWh/m²). The reason for this is the insulation level in Toronto is higher than in Calgary. This is also supported by the study done by Morrison Hershfield (2016) in literature.

Toronto heating energy is slightly higher than expected which is nearly equal to the savings in Calgary. The energy saving calculated is the overall saving from correcting all the thermal bridges listed in section 3. But the study does not tell how much improvement can be achieved by correcting any one of the thermal bridges. In the real world, the study of improvement of every single thermal bridge in the building would be more effective. This helps to know the thermal bridge which is more important and beneficial to improve rather than doing all the thermal bridges. The thickness of aerogel-enhanced blanket was either 10 mm or 20mm in thermal bridge correction for different construction system. The research would have been more effective to see change with different thickness of the aerogel-enhanced blanket. The thickness of aerogel-enhanced blanket might have an effect on the overall thermal bridge junction.

5.1.3. COST

With the use of aerogel-enhanced blanket for correcting thermal bridges, the major concern will be the cost of material. A simple cost analysis study of aerogel-enhanced blanket was done calculating the total area of aerogel blanket used in both constructions. The energy saving from the results and the cost of aerogel blanket were used for simple analysis as shown in appendix- 3. The cost does not seem so higher as the material cost payback period is approximately 20 and 13 years for concrete and steel building respectively. Thus, we came to a conclusion that even though the cost is higher, the limited use of aerogel blanket in thermal bridge detail will be beneficial. Apart from that, the aerogel-enhanced blanket price is decreasing annually with the increase of the aerogel market as stated in the literature (Koebel et al., 2012). From this, we can expect that the aerogel-enhanced blanket will be more beneficial in terms of the cost in upcoming years.

5.2. HOW ARE THERMAL BRIDGES CALCULATED FROM EQUIVALENT U-VALUE METHOD DIFFER FROM THE 3D DYNAMIC METHOD?

5.2.1. 3D DYNAMIC VS EQUIVALENT U-VALUE METHOD

This section will discuss the findings obtained from two different modelling approaches, 3D dynamic method and equivalent U-value method. Observing the results, it was found that the heating load calculated from the 3D dynamic method is always more than simulated from the equivalent U-value method. Equivalent U-value method underestimates the space heating load whereas overestimates the cooling load which is similar to the previous studies (Baba & Ge, 2017; Baba & Ge, 2016). Figure 16 and 17 demonstrate the comparison in percentage difference of the energy demand calculated using equivalent U-value method and 3D dynamic method for concrete and steel building respectively. Percentage was calculated based on building with no thermal bridge.

For accounting the effective U-value of the envelope, 3D dynamic method is better than the equivalent U-value method. This is because the 3D dynamic method takes into account the thermal inertia effect. The thermal inertia effect has a greater impact on the space heating load whereas it is much lower in the cooling load. This is because the building simulated were in the heating dominated climate.

The difference of heating load between 3D dynamic method and equivalent U-value method is up to 14-21% in concrete building and 15-22% in the steel building. And the cooling load difference was found to be 1-5% in concrete building and 3-7% in the steel building. With the use of aerogel-enhanced blanket to correct the thermal bridges, the discrepancy in annual heating loss decreases. It was found that the difference between 3D dynamic and equivalent U-value method is reduced to 9-13% and 0-4% respectively for concrete building. Whereas for the steel building, the discrepancy between 3D dynamic and equivalent U-value method is reduced up to 8-12% and 0-4%. The reduction of the discrepancy is due to the improvement of the thermal bridges. As a result, it also reduces the thermal inertia effect in the building. From the literature studies, the thermal inertial effect not only changes the resistance but also changes the dynamic behaviour of the wall which is consistent with the finding from the comparison of 3D dynamic method and equivalent U-value method. The decrease in difference suggests that the equivalent U-value method can also give accurate results if the details are improved. The improved details not only save the energy demand but also avoid the complex and time-consuming 3D dynamic method.

The graph in fig 16 shows the comparison of the annual heating and cooling load percentage differences between 3D dynamic and equivalent U-value of a concrete building with standard and aerogel-enhanced blanket improved details. With the presence of thermal bridges in the building, the heating load increases by 5- 10% using equivalent U-value method whereas, the percentage increases up to 16-32% when simulated using the 3D dynamic method. The annual heating load by 3D dynamic method was up to 22% higher than that calculated from the equivalent U-value method. Whereas, the cooling load calculated from the 3D dynamic method was up to 4% less than equivalent U-value method.

Figure 16: Comparison of annual space heating and cooling energy demand between equivalent U-value and 3D dynamic method for concrete building.

For the steel construction, the implementation of thermal bridges in the building increases the annual heating load by 8-14% and a reduction of annual cooling load up to 1- 14 % through equivalent U-value method. The annual heating load by 3D dynamic method was up to 22% higher than that calculated from the equivalent U-value method. Whereas, the cooling load calculated from the 3D dynamic method was up to 12% less than equivalent U-value method. The cooling load is comparatively lower than heating load which does not make much difference in total energy.

Figure 17: Comparison of annual space heating and cooling energy demand between equivalent U-value and 3D dynamic method for steel building.

The difference between 3D dynamic method and equivalent U-value method is found to be 14.28% for Vancouver(milder), 21.87% for Toronto and 17.16% for Calgary(colder) climate respectively in the concrete building. The results do not follow the pattern as the percentage difference is higher in Toronto rather than in milder or colder climate. The previous study done by Ge and Baba found that the milder the climate, the higher is the differences whereas it is inconsistent with the observation made in this research. Since Calgary has the higher heating and cooling load higher for the base building with no thermal bridge, the percentage difference is lower. This might be because of the level of insulation as the building insulation is kept the same in all the climatic zones. The more focused study of thermal bridges due to climate would be more effective if the level of insulation is kept to standard for all climatic zone.

5.2.2. WHICH IS MORE ACCURATE – EQUIVALENT U-VALUE METHOD OR 3D DYNAMIC METHOD?

Result in the study does not show the accuracy of the modelling approaches; 3D dynamic method and equivalent U-value method as no any comparison is done with the real building. Previous studies and literature suggest that the 3D dynamic method is the most accurate modelling method for the thermal bridges (Mao G. et al.,1997; Baba & Ge,2016; Baba & Ge, 2017; Ge & Baba,2017). This is due to the fact that 3D dynamic method allows the direct implementation of 2D or 3D connection details into the building energy model. Also, equivalent U-value method finds the effective U-value with thermal bridges but ignores the thermal inertia effect. Equivalent U-value method is the steady state condition which does not consider realistic condition as the 3D dynamic method. This also clearly supports that the result from the 3D dynamic method is more accurate. To confirm this, the results can be further tested doing the simulation of the real building and comparing with the real energy demand which is not easy. To get the accurate result, it is important to know the exact building materials properties, details and the construction methods of the building to be compared.

5.2.3. COMPUTATIONAL PERIOD AND EASE

Equivalent U-value method uses two software -THERM and WUFI Plus and 3D dynamic method only use WUFI Plus. In term of the computational period, it takes about 1-2 days for modelling the thermal bridges in THERM to get the linear transmittance value followed by less than an hour to simulate the model in the WUFI Plus in equivalent U-value method. However, the same WUFI Plus program after assigning the 3D thermal bridges takes up to 5 days depending on the complexity and materials in the thermal bridge details. Though the study by Ge and Baba (2017) concluded that the WUFI Plus simulation takes about a day, it was found to be much longer in the case that was modelled. The simulation time was up to four times higher than the previous study. The reason for the increased simulation time is mainly due to the material in the model, complexity and the number of thermal bridges. The time of simulation also depends on the computing capacities. According to the WUFI Plus, the material with a very low bulk density like air gap would slow down the simulation.

In my research, to gain the simulation speed the grid is set to coarse and accuracy was kept to the minimum. Apart from it, changes were made to the division of the grid to further expand. At the beginning of the research, the repetitive steel stud thermal bridges were modelled but the simulation could not be

completed even in 15 days, which was out of my time limitation. This was due to the fact that the whole building wall was created in 3D to show repeated stud. To overcome this issue, a new simplified model was created where the steel stud was not taken into account.

Since the 3D dynamic method gives accurate results compared to the equivalent U-value method, 3D dynamic method is more complex and time-consuming. It would be beneficial to avoid the complex method of modelling, if the details are improved. Apart from that, the inputs should be corrected to achieve more accurate results.

6. LIMITATION OF THE STUDY

Although this research provides insights into the opportunities of aerogel-enhanced blanket in concrete and steel building, the various limitation was encountered during the research. The details like the clear wall with stud, which become complex due to the repetitive 3D-element. With the implementation of such details in the building 3D simulation took comparatively longer time (around 15 days) which might not be possible for MRP and is tedious. All the 3D objects are remodeled for the simple configuration to reduce the run time of the model. Apart from that, to decrease the simulation time, the model was run with low accuracy and 3D object with the coarse option which might have some errors within it.

Another limitation is the thermal bridges junction and it's the base model. To ease the simulation as well as the simulation time, a simple two storied model was taken where the thermal bridges were considered in only one façade. Although the simulation is done for different orientation to check the difference in the building heating and cooling load, it was not done at the same model at the same time. This might affect the total percentage of improvement in the building. Similar to other modeling approaches, an assumption was made for the human activity and other conditions as specified in section 3.4. There might be some errors in the model as we don't actually know the mechanical ventilation, natural ventilation as well as the user's appliances. But since the same value was assigned for all the model, this might not affect comparing the results due to thermal bridges.

7. CONCLUSION

In this research, the aerogel-enhanced blanket of 10/20mm was used to improve the construction details in two different building type. A significant reduction of the heating load was observed with the application of aerogel-enhanced blanket in the building. This study shows that the aerogel-enhanced blanket can provide a better opportunity for the thermal bridging correction as it lowers the building heating by 6-8% in concrete building and 11-18% in the steel building. This shows that aerogel-enhanced blanket with thickness 10/20mm can be used as a thermal break in new as well as retrofit buildings. The more improvement can be achieved with increased thickness. Due to high thermal performance, low density, weight, and thickness of aerogel enhanced blanket, it can be applied airspaces and the areas with space and weight constraints.

The two different modeling approaches in the building suggest that the equivalent U-value underestimates the heating energy whereas, overestimates the cooling load. 3D dynamic method is more accurate than the equivalent-U-value method for proper calculation of the energy demand. The difference between 3d dynamic method and equivalent U-value method decreases when the details are improved with the aerogel-enhanced blanket as the dynamic effect of the thermal bridges will be reduced. For standard details, 3D dynamic method is required for accurate results whereas if the details are improved, equivalent U-value method also can predict accurate energy demand.

APPENDICES

Appendix 1: Heat flux of standard and improved details obtained from THERM simulations.

Standard concrete: Balcony detail

Improved concrete: Balcony detail

The detail shows a balcony section of building. Aerogel enhanced blanket was applied to avoid the heat flow through the continuous concrete slab.

Standard concrete: foundation detail

Improved concrete: foundation detail

The continuity of the concrete makes a pathway creating thermal bridges. The aerogel strip would help to stop the heat flow from the concrete from exterior surface.

Standard concrete: Shelf angle detail

Improved concrete: Shelf angle detail

The connection between the metal shelf angle and concrete has created a thermal bridge. The aerogel-enhanced blankets is used in between the shelf angle and the concrete slab as the thermal break.

Standard steel: window detail

Improved steel : window detail

The thermal performance can be further increased by increasing the thickness of the insulation, providing aerogel strip around the whole window perimeter.

Standard steel: balcony detail

Improved steel: balcony detail

The aerogel-enhanced blanket in metal angle connection to the exterior steel balcony slab. This helps to improve the interior surface temperature.

Standard steel: Shelf angle detail

Improved steel: Shelf angle detail

The detail below shows that the aerogel blanket in between two metal angles avoid the heat transfer creating a thermal bridge.

Standard steel: roof detail

Improved steel :roof detail

The detail shows a steel roof section which was improved using the aerogel blanket by avoiding the contact of the steel section from exterior to the interior steel section.

Appendix 2: Calculation of the Psi value.

Table 18: Calculation of linear thermal transmittance value for concrete building details

Description	2D model				Simplified Component A				Simplified Component B				Psi	
	U W/m2K	L m	dT K	ULdT W/m	U W/m2K	L m	dT K	ULdT Wm	U W/m2K	L m	dT K	ULdT W/m	Psi W/m	Psi W/mK
Concrete Balcony	0.3104	3.15	39	38.13264	0.254	1.059	39	10.49045	0.254	1.059	39	10.49045	17.15173	0.44
Improved Concrete Balcony	0.1876	3.15	39	23.04666	0.254	1.059	39	10.49045	0.254	1.059	39	10.49045	2.065752	0.05
Foundation	0.6199	1.899	39	45.91041	0.254	1.324	39	13.11554	0.4805	1.138	19.3	10.55341	22.24146	0.57
Improved foundation	0.4419	1.899	39	32.72756	0.254	1.324	39	13.11554	0.4805	1.138	19.3	10.55341	9.058598	0.23
Floor Junction	0.2438	3.036	39	28.8669	0.254	1.044	39	10.34186	0.254	1.044	39	10.34186	8.183167	0.21
Improved floor junction	0.2025	3.036	39	23.97681	0.254	1.044	39	10.34186	0.254	1.044	39	10.34186	3.293082	0.08
Shelf Angle	0.3708	3.078	39	44.51157	0.254	1.10474	39	10.94355	0.1934	1.04572	39	7.887448	25.68057	0.65
Improved Shelf Angle	0.2221	3.078	39	26.86133	0.254	1.156	39	11.45134	0.254	1.04572	39	10.3589	4.85109	0.12
Window	0.92	1.3	39	46.644	0.6	0.98	39	23.03	0.25	1.05	39	10.2375	13.3765	0.33
Improved Window	0.69	1.3	39	34.983	0.3	0.98	39	23.03	0.14	1.05	39	5.733	6.22	0.15

Table 19: Calculation of linear thermal transmittance value for steel building details

Description	2D model				Simplified Component A				Simplified Component B				Psi	
	U W/m2K	L m	dT K	ULdT W/m	U W/m2K	L m	dT K	ULdT Wm	U W/m2K	L m	dT K	ULdT W/m	Psi W/m	Psi W/mK
Floor Junction	0.2661	3.695	39	38.34634	0.1469	1.166	39	6.680131	0.4805	1.138	39	21.32555	31.66621	0.81
Improved Floor Junction	0.107	3.695	39	15.41924	0.1469	1.166	39	6.680131	0.4805	1.138	39	21.32555	8.739104	0.22
Steel balcony	0.425	2.72	39	45.084	0.1469	1.36	39	7.791576	0.1469	1.39	39	7.963449	29.32898	0.85
Improved steel balcony	0.2193	2.72	39	23.26334	0.1469	1.39	39	7.963449	0.1469	1.39	39	7.963449	7.336446	0.22
Roof Parapet	0.8954	1.729	39	60.37772	0.1469	1.191	39	6.823358	0.16	0.637	39	3.97488	49.57948	1.27
Improved roof parapet	0.2424	1.729	39	16.34527	0.1469	1.191	39	6.823358	0.16	0.637	39	3.97488	5.547036	0.14
Window	1.0324	0.914	39	36.80093	0.1469	0.914	39	5.236397	0.25	1.05	39	10.2375	21.32703	0.55
Improved window	0.4013	0.914	39	14.30474	0.1469	0.914	39	5.236397	0.14	1.05	39	5.733	3.335342	0.09

Appendix 3: Overview of cost of aerogel-enhanced blanket, annual savings and the expected payback period.

The quantity of aerogel-enhanced blanket required for thermal bridge correction were calculated for both building type. The table 20 shows the total area of the 10 mm aerogel enhanced blanket used for improving the details in concrete and steel building was calculated. The price of aerogel-enhanced blanket was taken as \$ 10.83 per sq. ft (Aerogel Technologies, 2018). The prices are calculated for the Ontario electricity rate. (Ontario, 2018)

Table 20: Calculation of payback period of the cost of aerogel-enhanced blanket

Building type	Area (m2)	Cost per m2 (\$)	Cost of aerogel (\$)	Annual saving (KWh)	Annual saving (\$)	Payback period(yr)
Concrete	196	119.93	23,512	12360	1124	20.9
Steel	282.6	119.93	33,892	28000	2520	13.44

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