THE IMPACT OF WINDOW-RELATED THERMAL BRIDGING ON ENERGY USE IN MURB RETROFITS
USING 2-D HEAT TRANSFER MODELLING FOR FULL WINDOW THERMAL BRIDGE ANALYSIS

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The Impact of Window-Related Thermal Bridging on Energy Use in MURB Retrofits –
Using 2-D Heat Transfer Modeling for Full Window Thermal Bridge Analysis

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Abstract

There is significant in the GTA for GHG emissions reduction through energy retrofit measures of the more than 2000 post-war multi-unit residential buildings. Overcladding is an effective energy reduction strategy; however, it is crucial to properly detail window installation to avoid thermal bridging in a retrofit situation, as there may be excessive heat loss and condensation at this junction. This paper examines the thermal bridging potential at the window-wall interface in an EIFS overcladding retrofit scenario for a typical MURB retrofit. The research used the software THERM to compare influence of three typical window-wall interface on the energy performance of the window and wall. The analysis examined the position of the window within the frame, insulation placement around the window perimeter. It was found that window placement within the wall section and detailing at the opening do significantly affect the wall's overall thermal performance, determining that design improvement should be considered and quantified in retrofit energy reduction strategies.

ACKNOWLEDGEMENTS

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Dedication

This MRP work is dedicated to my husband, David. You have been a constant in my life and a foundation of patience and love during the challenges of graduate school and life. I am deeply thankful for having you in my life.

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ABBREVIATIONS USED

COG: Center of Glass

ECM: Energy Conservation Measure

EIFS: Exterior Insulating Finishing System

EPS: Expanded Polystyrene Insulation

GHG: Green House Gas

IEQ: Indoor Environment Quality

IGU: Insulated Glazing Unit

MURB: Multi Unit Residential Building

PHI: Passive House Institute

PHPP: Passive House Planning Package

WWR: Window Wall Ratio

XPS: Extruded Polystyrene Insulation

SYMBOLS USED

Ψ-value: Psi-value; the difference in linear thermal transmittance between isolated and installed thermal coupling coefficients (W/mk)

L_{2D}: Thermal Coupling Coefficient – modelled U-value (W/m^{2}K) multiplied by the modelled linear dimension(m) (W/mK)

U: One-dimensional thermal transmittance (W/m^{2}K)

$U_{2D:}$ Overall thermal transmittance taking into consideration installation Ψ-value (W/m^{2}K)

A: Area (m^2)

W: Width (m)

H: Height (m)

Introduction

The existing residential and commercial building stock is a major contributor to Green House Gas (GHG) emissions. It is estimated that buildings use 40% of primary energy in North America, contributing 24% of GHG emissions (Ueno, 2010; Kosny et al. 2014). Thus, it is crucial to invest in improving the existing building stock if ambitious GHG reduction goals are to be met.

More than 50% of all dwellings in Toronto are contained in multi-unit residential buildings (MURBs) (Touchie et al. 2013). These post-war dwellings are still structurally sound but have markedly obsolete energy efficiency standards. There are more than 1000 concrete frame MURBs in Toronto. Built between the 1950s-1970s, most of these are not insulated and are very energy inefficient by any standard (Mayors Tower Renewal, 2008). High-rise residential buildings are one of the leading sources of CO_2 emissions, they are also responsible for an estimated 17% of annual total GHG emissions associated with natural gas and electricity; this must be reduced in order to meet the city's GHG reduction goals (Touchie et al., 2013). Retrofit of these buildings will result in an estimated 3-5% Total GHG emissions reduction within the city (Mayor's Tower Renewal, 2008); Thus, Toronto MURBs present themselves as a prime target for energy reduction measures, as current research has motivated initiatives for massive MURB renewal in the city (Kesik & Saleff, 2005).

There are ever increasing demands from energy efficiency standards such as OBC SB-10 and Toronto Green Standard to mitigate unnecessary energy use in our buildings. For example, the Toronto Green Standard Requirement for GHG emission reduction – *"…design the building(s) to achieve at least 25% efficiency improvement over the Model National Energy Code for Buildings (MNECB) or 13% over the Ontario Building Code"* (City of Toronto, 2010). As a consequence, stringent energy conservation measures deem the buildings ready for energy retrofits after 20 to 30 years, even though building structures are often good for at least 60 years, (Konstantinou et al., 2011).

In the field, it is understood that using a prescriptive U-value in building codes and guidelines does not account for the heat loss from thermal bridges such as at the window-wall junction (Morrison Hershfield, 2015). The prescriptive approach allows for discrepancy between estimated and actual energy use through the disregard for linear thermal losses in benchmarks (Morrison Hershfield, 2015). Linear thermal transmittance comprises energy losses due to variation in the construction assembly through changes in structure, material or geometry. Even though building components are increasingly efficient, this is not the case for improvements in interface detailing (Asdrubali, et al., 2012). While current standards do not properly account for losses due to thermal bridging, there is increased concern in addressing the problem, as the environmental and economic impacts of excessive energy use in our buildings become evident. Currently, BC Hydro has commissioned a comprehensive analysis of common thermal bridges, and has produced a database of best practice details in the BETA Guide (2014). This broad and comprehensive study offers energy and cost impacts for various detailing options. As the BETA Guide (2014) outlines, the complex detailing at window-wall junctions can have considerable impact on the linear thermal transmittance at this interface, and there may be a use for designers to have a relatively easy method to assess detailing decisions. This would be especially useful for retrofit scenarios as there are peculiarities in older building stock that need to be addressed in a customized manner.

When assessing how fenestration influences energy use in a building, there are two main factors to investigate. The common metric to address is the product performance. The performance standards for windows are complex, as the U-value for fenestration differs when temperature and surface air film coefficients change (Hanam et al., 2014). Thus, standardization requires that windows be assessed within a commensurate context. For instance, Passive House Institute (PHI) window certification uses climate specific boundary conditions, and windows for buildings in colder climate zones have more stringent boundary condition requirements. The different boundary conditions adopted by American or European standards will affect the predicted performance of any manufactured fenestration product, hence rendering the whole analysis process that much more complicated (Hanam et al., 2014).

The second, and less common metric to address, is the installation detail of the window, and the resulting thermal bridging effect. The ISO (2007, as cited by Barnes et al., 2013) defines thermal bridging with 3 criteria: “(1) full or partial penetration of the building envelope by materials with a different thermal conductivity, and/or (2) a change in thickness of the fabric, and/or (3) a difference between internal and external areas, such as occur at wall/floor/ceiling junctions”. The window-wall junction fulfills all three criteria, thus rendering it an elaborate detail to assess (Barnes, 2013). In the current Canadian Building Code, the complex factors of window related thermal bridges are not adequately addressed (Barnes, 2013). For instance, a commonly used area-weighted U-value assessment considers only the wall and window u-values in isolation, and does not incorporate thermal bridges related to the window installation, which represent a complex, 3-dimensional heat flux, and require careful analysis to accurately account for them (Barnes et al., 2013). Thermal bridging of the frame at the window edge is typically accounted for in ISO standards (Hanam et al., 2014). But, because installation detailing is variable and designs can often be custom, the thermal transmittance due to the window-wall thermal bridge is not standardized (Barnes et al., 2013). In fact, the only standardization process that requires window-wall installation thermal bridging to be accounted for is the PHI accreditation (Hanam et al., 2014).

That being said, it is important for designers and contractors to have a detailed knowledge of how their specifications will affect the performance of the building envelope – not only in energy performance, but also for occupant comfort and indoor environment quality (IEQ).

The State of Toronto MURBs

Figure 1*(A-B): Common Deterioration points in the GTA MURB building envelope; Brick Spalling (left) and concrete deterioration (right). Photos by the author*

According to Tower Renewal researchers Kesik and Saleff (2009), a common envelope system for post-war MURBs is a 100mm (4”) non load-bearing brick veneer over four-inch concrete block back-up wall (Figure 3). This may or may not have interior insulation, and often, the masonry envelope is laid on top of an exposed exterior floor slab perimeter. This assembly is not an energy efficient design by any standard, buy further weak points that contribute to poor energy performance of Toronto’s aged MURB stock include single-pane windows, deteriorating sealant, and poorly insulated walls. This combination of substandard elements results in excessive air leakage and thermal bridging throughout the building envelope (Kesik & Saleff, 2009).

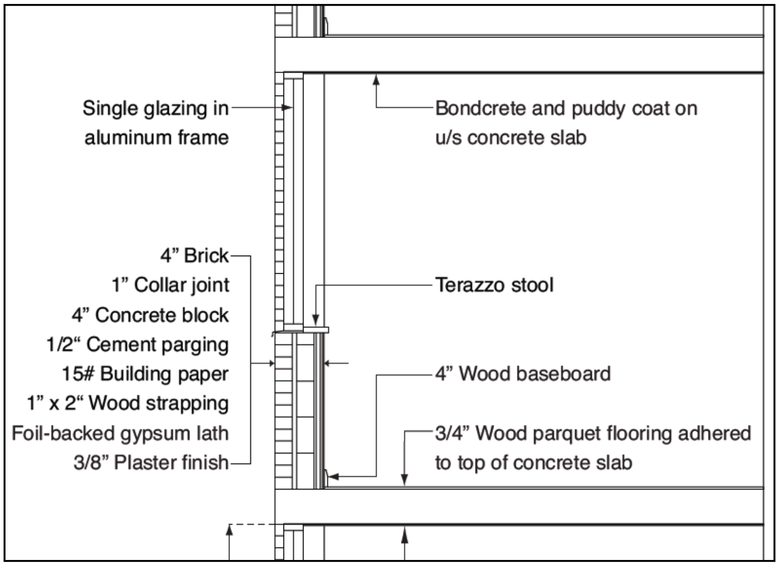


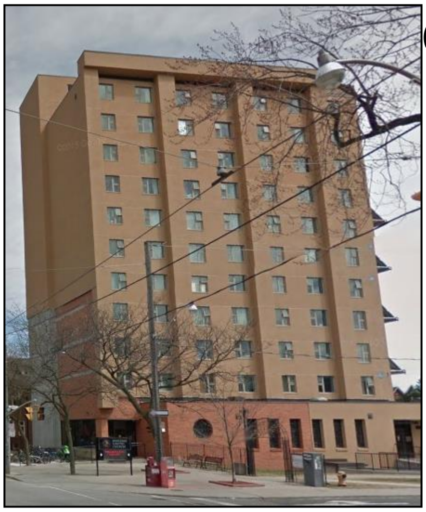
Figure 2: *Typical wall assembly for MURBs built during the 1960-1980's (Kesik & Saleff, 2009)*

A typical overcladding renovation procedure will involve the installation of a manufactured non load-bearing exterior insulating finishing system (EIFS) over the existing structure, with the replacement of single-pane or otherwise deteriorated windows with high-performance double pane windows. This process addresses the shortcomings mentioned and is among the most common and effective of the energy conservation measures (ECMs) available to the Toronto MURB stock (Touchie et al., 2014).

Overcladding retrofits can improve thermal losses by up to 85% (Kesik & Saleff, 2005). Also, with growing technology, more demanding energy reduction goals and high-performance building components, it has become important to know how to install components so as to optimize these costly renovations. Addressing details to mitigate thermal bridging at junctions is an effective way to make sure high performance elements in the building envelope are being used in the best way. Improving details and minimizing thermal bridging can result in up to 10% further energy reduction, and this can be done before considering more insulation or triple glazed windows (BETA Guide, 2014, as cited by Ge et al., 2015).

On the other hand, inadequate detailing can result in poorer energy performance and lower surface temperatures at the window than expected. Aside from lower overall energy performance, thermal bridges will result in lower surface temperatures at the window frame edge. This phenomenon may potentiate condensation, which, if sustained, can lead to mould growth, reduced indoor environment quality, and premature building envelope deterioration (Totten, 2008).

Two Case Studies


(A)


(B)

***Figure 3**(A): Green Phoenix, Toronto. Photo source: googlemaps.com, (B) Thorncliffe Park. Photo taken by author*

Two case studies were referenced for the purposes of this study. The buildings are undergoing or have recently undergone an EIFS overcladding retrofit with window replacement. Of interest for the research were the investigation of the typical details currently used at the window-wall interface. This detail is susceptible to thermal bridging losses.

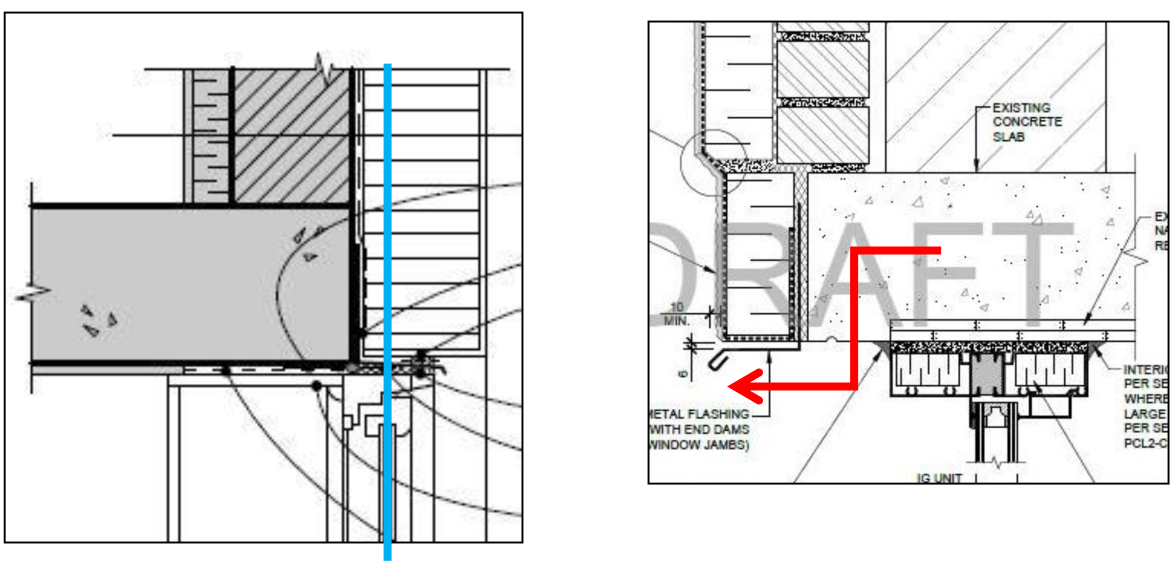


***Figure 4**(A): Green Phoenix header detail: insulation in line with IGU; (B): Thorncliffe header detail: frame is inset, allowing thermal bridge at slab. See **Appendix 1** for sill details of these projects.*

Literature Review

With increased motivation to improve energy standards in the existing building stock, there is a growing body of research on how building envelope retrofits should be detailed to optimize the energy savings outcomes. Furthermore, these investigations extend to concerns regarding IEQ and the potential to mitigate condensation risks in buildings that have been underperforming, not only in energy use, but also in occupant comfort standards. There is mounting research investigating the impacts of thermal bridging on energy load (Kosny et al., 2014; Ibrahim et al., 2014; Ge et al., 2015)), condensation risk (Nelson et al., 2011; O'Brien, 2005), and air-leakage (Maref et al., 2011). Other studies have carried out sensitivity analyses to offer best practice design solutions in the effort to minimize thermal bridging (Barnes et al., 2013; Cappozoli et al., 2013; Morrison Hershfield, 2015); and others looking at workmanship on detailing quality in order to curb thermal bridging in construction (Wang, 2015). There have also been a number of studies scrutinizing the current methods of analysis for complex interface details (Sierra et al., 2015; Ascione et al., 2013; Berggren & Wall, 2013). There has been more limited research on optimizing details in retrofit scenarios. Ueno (2012) looks at a number of case studies to determine best practice solutions for window interface thermal bridging in deep-energy retrofits of wood frame houses. Kosny et al. (2014) focus on solving linear thermal losses using vacuum insulated panels in overcladding retrofits rather than more cumbersome rigid insulation at the window surround. That said, both of the studies referenced above suggest that there is still a need in the industry for practical, data-based solutions for thermal bridging at the window-wall interface, specifically for retrofit situations.

While fenestration technology has improved standard window performance considerably, this is not the case for detailing quality in the design and installation phases – issues which can undermine the improvements gained by using high-performance windows (Cappalletti et al., 2011, Wang, 2015). Moreover, there is still a lack of clarity in the field regarding the effect of detailing on heat loss at the window-wall interface; the impact of windows on overall performance is often limited by only concerning the influence of window-wall ratio, and product performance (Asdrubali et al. 2012).

Current practices in mitigating window-related thermal bridging

Firstly, an explanation is required to distinguish the clear wall to the interface condition. Clear wall is the assembly of components making up with wall, comprising the structure, insulation, and finishes, including any constant thermal bridge elements such as structural elements.

Interface details represent a change in material or geometry that interrupts the homogeneity of the wall (Morrison Hershfield, 2015). Window penetrations are one of the most influential and unavoidable interface details in the wall assembly.

Current ASHRAE Standard 90.1 calls for a prescriptive U-value that does not consider the heat loss from interface detail thermal bridging – this means that designers are not required to consider them, there is little incentive to consider them, and the result is that the nominal U-Value for a wall assembly may be significantly different than the actual building performance (Morrison Hershfield, 2015). The BETA Guide (2014) reports that, even with efficient details of their recommendation, heat loss due to slab, parapet and window interface thermal bridges will de-rate the clear wall U-value by 35-140%. Though the range of impact is vast in their research, and the influence of window-related thermal bridging is dependent on window-wall ratio, the numbers are still substantial, even at the low estimate. When it comes to window detail thermal bridging, the BETA Guide clearly outlines the relative impact of interface design on thermal transmission of the window connections. Even small detail changes can influence the thermal transfer at this complex connection. For example, their analysis of window-wall interface details offers this scenario: If the installed linear thermal transmittance can be decreased from 0.32 W/mK to 0.19 W/mK (a 40% improvement) on a MURB with 40% glazing, this is equivalent to going from a U-value of 0.63 W/m2K to 0.52W/m2K (or R-9 to R-11) in improving thermal resistance of the wall. (Morrison Hershfield, 2014). The authors address design solutions that demonstrate the relative impact of detail variance of the linear thermal transmittance. Figure 4 shows that insulation at the sill opening can cut the Ψ-value nearly in half.

In order to encourage designers to consider thermal bridging heat losses, detailed simulation testing is required, and it is important that they are comparing their results to a base case that

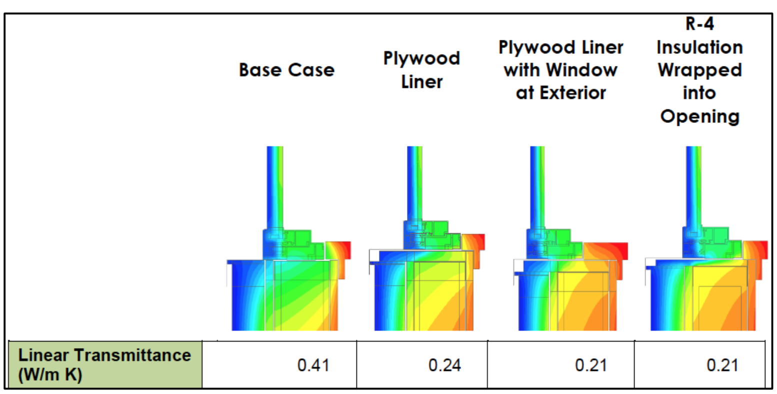


***Figure 5**: Influence of interface detailing on linear thermal transmittance (Ψ-value) at the window-wall junction. (Morrison Hershfield - BETA Guide, part 3, 2014)*

accounts for heat loss from these thermal bridges (Morrison Hershfield, 2015).

There are a number of tests which demonstrate that fenestration products perform better in isolation than in the installed state (Misiopecki et al., 2013; Capalletti et al., 2011; Barnes et al., 2013; O'Brien, 2005; Totten et al. 2008). Totten et al. (2008) claim that the installed thermal bridge effectively undermines the more efficient window designs by impairing the tested performance of the fenestration unit. This study examines a number of details that cause thermal bridging, including the window-wall interface, and it demonstrates through simulation (Figure 5) that testing a window frame in isolation of its connection to the wall compromises the accuracy of the thermal bridge and underestimates the heat loss.

The study also proposes that increased thermal insulation at the interface can help reduce further the thermal bridge; other research agrees with this finding.

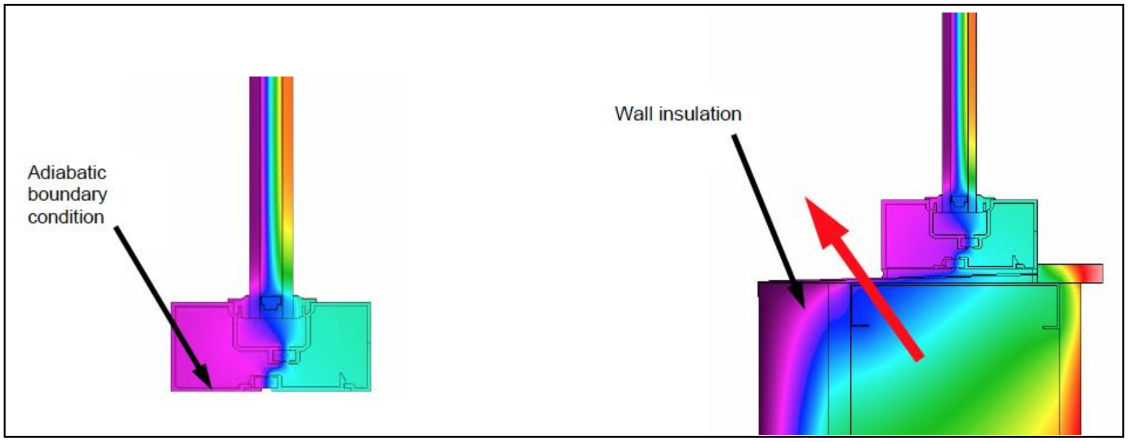


Figure 6: *The thermographic model demonstrates the heat loss that must be accounted for in the detailing of window to wall interface. (Source: Totten et al. 2008)*

A study by O'Brien et al. (2013) demonstrated similar results in its study examining the accuracy of product performance metrics. This study was specifically looking at the condensation resistance factor and whether isolated product tests can reliably be used to assess risk. Figure 6 shows a demonstrable temperature difference of almost 5°C when an installation condition is introduced

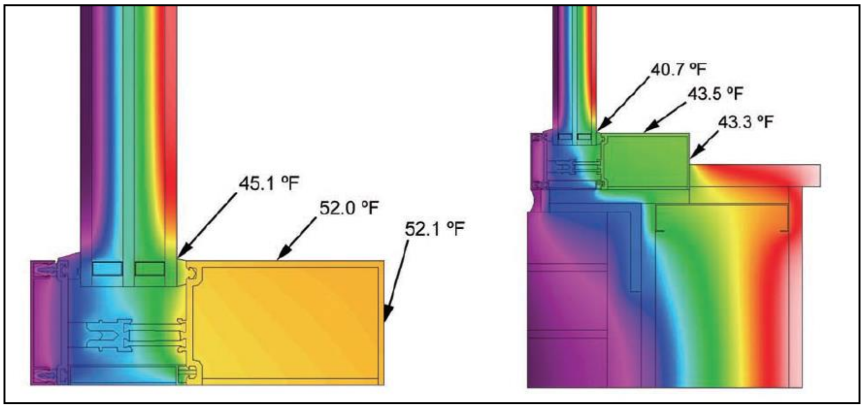


Figure 7: *Demonstrates the temperature discrepancy when an adiabatic boundary is forced on the frame edge, rather than using an installation condition for simulation. 11.2°C (52.1°F) verses 6.3°C (43.3°F) (O'Brien, 2005)*

Quantifying window-related thermal bridges

In order to standardize and streamline thermal bridges in building performance analysis, there needs to be comprehensive and consistent methodology in how it is accounted for. Unfortunately, there are currently a number of discrepancies in how different bodies of research go about assessing thermal bridges in the building envelope; and there is assertion within the research that the current methods for accounting for thermal bridging are inadequate (Ascione et al. 2013, Berggren, 2013, Ge et al. 2015, O'Brien et al, 2005, Sierra et al. 2015).

Ascione et al. (2013) assert that current building simulations are largely 1-dimensional and fail to evaluate multi-dimensional heat loss effects at all. Though ISO standards present methods for evaluation of thermal bridges by following rigorous demands of the EPBD (Energy Performance of Buildings Directive), the complex simulation and auditing required to improve energy use estimations can be onerous for designers. The authors propose a compromise of a simplified multi-dimensional simulation for energy auditing. Though a viable compromise between incomprehensible multi-dimensional simulation and over-simplification is crucial to make accurate energy assessment mainstream, this method remains somewhat cumbersome for common use in the design world. Berggren et al (2013) stress the importance of clarifying misunderstandings in different methodologies used for thermal bridge assessment. With growing awareness of the impact of thermal bridge heat loss, it is crucial that proper methodologies be standardized to curb growing discrepancies in data. For example, the use of simplified methods that don't consider the relative verses absolute impacts of thermal bridging may leave designers unaware that thermal bridging is most impactful in super-insulated scenarios (hence the importance of thermal bridge assessment for PHPP).

As mentioned, a number of variables play a role in how the installed window performs as compared to its predicted performance. These factors include: placement of the window within the wall section, insulation thickness in the wall, insulation placement in the wall section, having a bridged or un-bridged sill, whether the sill and frame edge are insulated (Cappalletti et al., 2011, Misiopecki et al., 2013; Ibrahim et al., 2014; Capozzoli et al., 2013). But how important are these decisions to the overall performance of the building envelope. Are “lesser” details making a significant impact on the thermal losses through the envelope?

There are a growing number of studies investigating the importance of this complex junction in terms of linear thermal heat loss, overall impacts on the building envelope, as well as targeting solutions for how thermal bridging can be controlled. High variability within the industry in building envelope and fenestration design makes this issue problematic to streamline and standardize. Passive House Institute (PHI) is currently the only standard that requires the installed window thermal bridge to be measured (Hanam et al., 2014). While building envelopes are being designed with better insulating and air tightness measures, the relative heat loss from thermal bridging at the window junction is more impactful to the overall performance than previously thought. The relative heat loss due to thermal bridging can be four times higher in a super-insulated house as compared to a standard house (Cappozoli et al., 2013). A study by Berggren et al. (2011) also found that relative heat loss due to thermal bridging increases as more insulation is added to the exterior wall. This would mean that, with lower rates of air exchange, the risk of condensation rises if the thermal bridge is not mitigated. This outlines one main concern with controlling this linear heat flow. There are a number of studies that have focused on comparing the isolated U-values of the window assembly to the installed thermal losses. This comparison may seem trivial, but, as mentioned, building envelopes are becoming super-insulated and increasingly airtight, rendering the thermal bridge losses increasingly impactful. It is agreed among the research that the degree to which the window-wall interface influences the overall U-value for the window is significant and should be considered going forward (Cappalletti et al., 2011; Misiopecki et al, 2013; Barnes et al., 2013).

Cappalletti et al. (2011) calculated linear thermal transmittance for the interface details at jambs, head and sill, and apply these values to the perimeter length of the fenestration unit in order to calculate overall heat loss at the junction between window frame and wall. The study was comprehensive and their findings broad; they concluded that the overall performance of the window is dependent on the complexities of detailing, and cannot be established merely by factoring a number of isolated performance metrics. Frame position within the wall section and insulation placement is shown in this study to significantly affect the linear transmittance. Overall improvements range from 52-76%, depending on other detail variables such as where the frame insulation is placed (interior, intermediate, or exterior), and whether there is insulation wrapped at the frame edge. By conducting a relatively comprehensive analysis, Cappalletti et al. found that changing the placement of the frame from interior to exterior of the wall section consistently had more beneficial effect on the Ψ-value than adding sill insulation. The study found that moving the frame form the interior to exterior of the wall section decreased the Ψ-value by 76%, while adding insulation at the sill decreased the psi-value by a maximum of 56%. Even though the specific details are developed for a warm climate, and thus do not follow best practices for cold climate conditions, the findings have use, especially to what extent window installation effects thermal performance. Using as a base value the ISO thermal rating of the isolated window (1.458 W/m^{2}K), they determined the magnitude of influence the installation position would have on its thermal performance.

Table 1 illustrates the proportional losses based on detail variation. As a solution to dealing with unaccounted for thermal losses, the authors propose that the installation detail be part of window performance metrics.

***Table 1**: Increment heat losses due to window-wall interface detail*

Base Case: U_{window} = 1.458 W/m2K		*Overall window Thermal Transmittance (W/m2K)*	*Increment losses (%)*
External Frame Position	Non-insulated	1.625	11.5
	Insulated to frame	1.588	8.9
	Insulated above frame	1.54	5.6
Intermediate Frame Position	Non-insulated	1.929	32.3
	Insulated to frame	1.644	12.7
	Insulated above frame	1.607	10.2
Internal Frame Position	Non-insulated	2.13	46.2
	Insulated to frame	1.755	20.4
	Insulated above frame	1.694	16.2

Source: Cappalletti et al., 2011

The research generally supports the idea that window placement is one of the most influential factors for window-wall interface thermal bridges. Misiopecki et al. (2013) look at a range of variables affecting details in a window-wall connection and the impact on linear thermal transmittance on a well-insulated wall. The paper aims to see if the position is important for highly insulating windows. The researchers modified clear wall insulation thickness, distance of the frame edge from exterior wall plane, and the internal sill insulation thickness.

For this study, only the frame's interaction with the sill was examined, a simplified wall section was used, and the IGU was replaced with a calibration panel, which is the practice in ISO standard when determining the frame's U-value (Hanam et al. 2014). Finally, they investigated the magnitude of influence the thermal bridge would have on varying window size. This study offers a comparative analysis, whereby the researchers have simplified the model to such a degree that there is room to expand on their findings with increased wall detail and further analysis of the jambs and header to more accurately determine the impact of the frame to wall junction on thermal losses. A sensitivity analysis is one that aims to quantify the magnitude of influence a variable will have on the outcome of the test performed. This is s useful approach in studying window interface thermal bridges, as the variables are many and entwined within the logic of detail design for the designer.

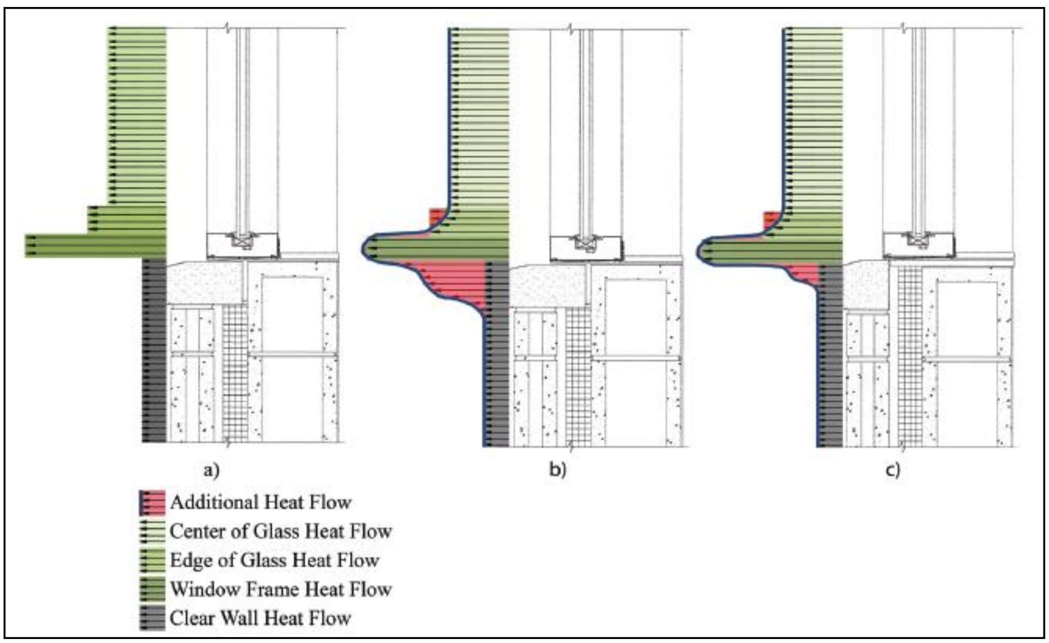


***Figure 8**: a) Heat loss accounted for when simple area-weighted U-values are assumed. b) & c) Heat loss accounted for when the linear thermal transmittance is considered. (Barnes et al. 2013)*

Barnes et al., (2013) also consider thermal bridges in the window assembly verses the thermal bridge resulting from installation. The authors focus on determining whether the installation thermal bridge can be attributed to the frame, or whether it should be considered as aspect of the sill detail (see Figure 7). This is achieved by comparing the linear thermal transmittance of different frames with two sill details, one thermally broken and one thermally bridged.

The sensitivity analysis found that a badly thermally bridged detail will not be effected by the frame choice. This is due to the fact that the heat flow path through the sill is not short-circuited through the frame. However, if the sill is thermally broken, a poor frame can affect the linear thermal transmittance considerably. A sensitivity analysis can be informative for designers to justify design decisions in Retrofit scenarios (Barnes et al., 2013; Capozzoli, 2013).

Capozzoli et al., (2013) conducted a sensitivity test on the impact of insulation placement, thickness and thermal mass of the wall, and the effect on thermal transmittance. As building envelopes become better insulated, and more air tight, the detail design will continue to have increased influence on the energy use of the building. The authors claim the importance of quantifying how detail improvements mitigate energy loss. They found that linear thermal transmittance at the window-wall junction is most impacted by the level of insulation. This study, however, does not adhere to a continuous thermal break between the IGU and the wall insulation, and boundary conditions for the test are unknown.

Window related thermal bridging and energy use

Ascione et al. (2013) discuss the common issues around current practices of calculating heat loss, and the lack of accuracy in accounting for thermal bridging during energy audits and in energy simulation

Improved building components are highly developed and there is a high standard of performance in window technology. Unfortunately, there is still a lack of rigorous oversight or standardization to control the thermal bridge at window-wall junctions**.**

A number of authors discuss the discrepancy between simulated performance and actual performance due to the inattention to thermal bridging effects on overall wall R-values (O'Brien et al., 2005; Barnes et al. 2013). The importance of predicting these thermal losses at the design stage and knowing the impact of design decisions on thermal bridging should not be underestimated.

Wang (2014) looks at thermal bridging and air leakage as functions of detailing and workmanship. The purpose of the study was to find out the combined effect of detailing on

thermal bridging and infiltration. His concern is the impact of construction detailing on thermal bridges. The research looks at overall thermal bridges on a façade and finds that only 38% of the façade is free of thermal bridging. The research concluded that adhering to good detail design is important to mitigate thermal bridging, and though it may have only a moderate effect on energy use, which is highly dependent on WWR, it is crucial in controlling condensation risk. Other studies have shown similar results. In a more general analysis of thermal bridging, it was found that, in a well-insulated building with high-performance windows, around 30% of the heat loss is through thermal bridges (BETA Guide, 2014, as cited by Ge, 2015).
Pelss et al. (2010) States that the simplified method used in ISO 14683 cannot be applied to low energy (passive house) solutions, as the thermal bridge atlas used in that standard differs too much from low-energy construction solutions. He found that total thermal bridging in a low energy house accounted for 7.7% of all heat losses, with window-wall junction interface being the highest contributing thermal bridge, responsible for 3.62% (with window wall ratio (WWR) of less than 20%); the percent impact of window thermal bridging is highly dependent on the WWR and fenestration perimeter length. Thus, in a typical MURB retrofit scenario with an existing WWR will be close to 50%, the impact of window-related thermal bridging may be significantly higher.

Though some literature indicates that thermal bridging at the window-wall junction has only a moderate impact on heat loss relative to other mechanisms, there still lacks definitive information on the impact of thermal bridging on energy consumption, perhaps due to the variation in construction modes and architectural detailing, as well as variation in analysis and modelling standards. It has been noted in the literature that thermal bridging can account for around 15% of heat losses in a recently built, typical building (Wang et al., 2014). Furthermore, the discrepancy between estimated and actual infiltration and thermal bridging is 60% on average (Wang et al., 2014). The values above relate to thermal bridging as a whole, however.

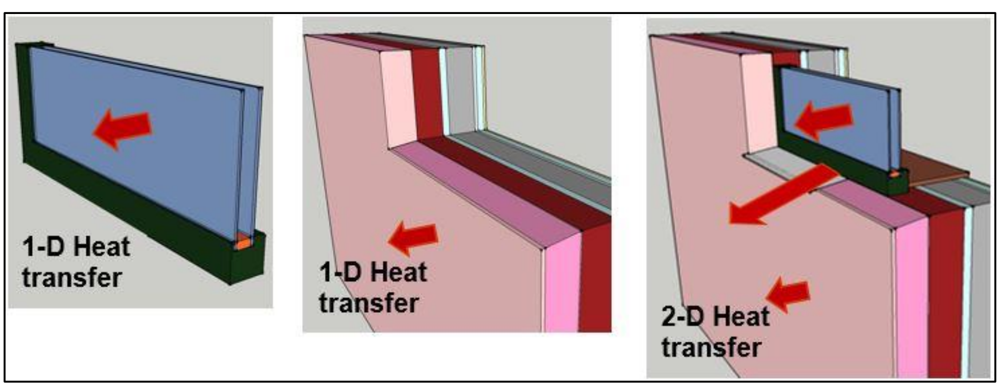


***Figure 9**: mitigating factors affecting window-related thermal bridging such as assumption of 1D heat transfer, window placement, geometry and WWR*

Quantification of thermal bridging losses on isolated components such as the window-wall interface is not typical due to the compounding complexity of high level of detail variation, window geometry, and WWR.

Nonetheless, with increased air-tightness, thermal bridging becomes a more serious problem as it is related to condensation. If cold surface conditions are left unaccounted for this can lead to condensation and deterioration in the building envelope (Totten, 2008). Thus, as the thermal resistance and air tightness of the building increase, so does the relative effect of the thermal bridge (Berggren et al., 2013; Cappozoli et al., 2013), it is now more important than ever to pay closer attention to the complexities of window-related thermal bridging.

Impact of thermal bridging on condensation risk

Window-related thermal bridges are complex and represent one of the largest thermal bridges in the building; and while fenestration products continue to improve in performance, the thermal bridging effects of the window-wall connection detail should not be underestimated for condensation, mould growth and deterioration risks (Sierra, 2015). A common practice in assessing thermal bridges at a sill or header detail is to replace the frame connection to the wall with an adiabatic plane. However, Sierra et al. (2015) insist that a more detailed assessment of linear thermal bridging is needed for determining condensation risk. In this study, it was found

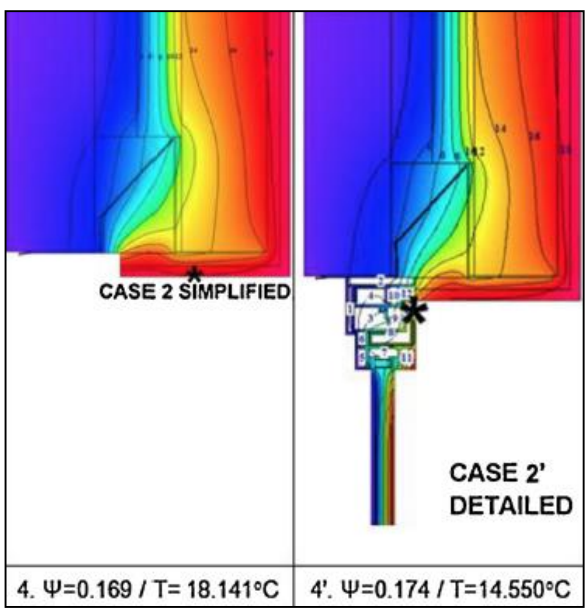


Figure 10: *Interior surface temperature comparison between simplified and detailed modelling. Source: Sierra et al. 2015*

that comparing simplified and detailed analyses of a window-wall interface revealed condensation risk in the detail model (where the frame and IGU were included in the thermographic test) that was not indicated in the simplified analysis (where the frame was replaced with an adiabatic boundary). Their finding concluded that the lowest temperature readings at the interior surface differed by around 3.6 °C, from 18 °C for the simplified method, to 14.5 °C for the detailed model (see Figure 8). This temperature difference is significant and indicates the usefulness of detailed analysis.

The condensation risk factor (CRF) is a rating system for fenestration products indicating the likelihood of condensation occurring on the surface, under certain climate conditions. However, there is some scrutiny to the applicability of this factor in actual conditions, due to the variability in details at the window frame to wall interface (O'Brien, 2005; Kudder et al. 2005). In a thermally broken frame situation, if the installation detail allows a heat conduction path that skirts the insulating plane, then the thermal break is undermined and will not achieve what the CRF rating indicates (Kudder et al., 2005).

The window-wall interface condition was assessed by Maref et al. (2012) who found that the thermal bridge in modern high-performance IGUs is worse at the frame to wall connection than at the glazing spacer. Modern windows are increasingly resistive to heat transfer, so the heat transfer path that must be carefully considered at this point is the installation detail.

Addressing Window-Related Thermal Bridges in Retrofits

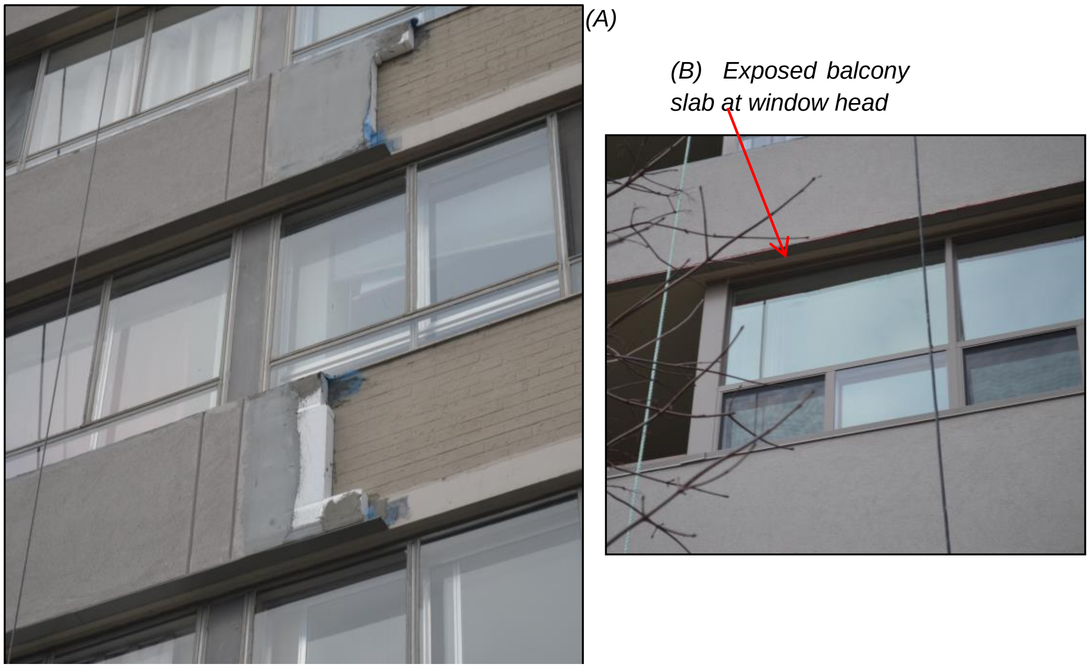


***Figure 11**: (A)Overcladding retrofit in progress, (B)Thorncliffe Park, Toronto. (Photos taken by the author, 2015)*

The International Energy Agency reports that existing buildings will continue to use the majority of all energy utilized by buildings (Kosny et al., 2014). As new buildings become more energy efficient, they will consume less than 1/5th of the energy. Thus, the importance of upgrading the current building stock in order to curb building energy use in a significant way is obvious. However, overcladding retrofits present peculiarities and design challenges, and the interface condition is a complex phenomenon (Kosny et al., 2014). Ueno (2010) discusses problems with window penetrations in super-insulation retrofit details, specifically interested in condensation risks. As thermal resistance and air-tightness are improved on the envelope, the relative impact of the thermal bridges that will still exist is increased (Ueno, 2010 Barnes, 2013).

According the Ueno, the window plane location and detailing need particular consideration as this thicker wall insulation is applied. The study lays out advantages of each system. It outlines the importance of drainage plane location, and creating practical construction solutions when choosing window placement. When creating a thicker wall assembly, it may require that the windows be detailed to account for the deeper wells, as well to create a continuous thermal break plane (Ueno, 2010). As this author observed, the re-detailing of window frames to be in line with the new insulation plane is not always the priority. This can be due to budget and time constraints, as discussed with building manager currently undergoing an overcladding retrofit

(Figures 9-10). The placement of the window along the non-structural exterior insulation plane requires further anchoring and drainage considerations (Ueno, 2010); the challenges of retrofit mean the pros and cons of internal placement of the frame and external placement details are not simply about heat loss. Challenges are not restricted solely to the thermal bridging issue, as drainage and air leakage potential cannot be overlooked during a retrofit; working with existing and sometimes imperfect scenarios presents multi-dimensional problems. Nonetheless, in retrofit situations, this detail is not always treated correctly and can result in serious thermal bridging that can impair the success of a costly undertaking.

Research Problem

There is a need for further investigation in the effects of window placement and detailing for retrofit and over-cladding scenarios. While new-build situations allow for an ideal detail design. The is interest in addressing a retrofit situation that requires careful consideration the as-built elements. In an attempt to help optimize overcladding retrofits, having a robust knowledge of how to deal with these imperfect situations is key, and one way to understand how to predict and prepare the best details for MURB retrofit and overcladding window to wall detailing is to thoroughly examine a range of window replacement details and determine how design detail decisions affect the overall performance of the wall assembly. There is still uncertainty in how to mitigate thermal bridges. In working through a full window 2-D analysis in order to isolate the linear thermal transmittance of the frame connection detail in three detail schemes, the goal of the research is to inform designers of a practical method for accounting for thermal bridges in window detail design.

Research Questions

There are still uncertainties regarding the influence building envelope energy performance, mould growth and condensation. With this lack of conviction in the current knowledge in the industry, there is a need to contribute to the knowledge base of how window-related thermal bridging is impacted by detail design.

1. In a typical installation detail, is the impact of window perimeter thermal bridging a significant contributor to thermal losses in a well-insulated retrofit wall assembly?
2. How much does detail variation impact these thermal losses?
3. Does the installation condition impact the surface temperatures significantly?

Methodology

Purpose of Study

This paper investigates the current typical retrofit details at the window-wall interface with 2D modelling software THERM to see if potential detail improvements will significantly increase the performance of this common thermal bridge. Through exploring the 2D modelling approach to investigate the thermal bridge variation in three detail options, the research aims to develop a method to use 2D thermal transfer analysis for informing window retrofit design detailing. Through the 2D analysis method, the paper will explore how much the detailing of a window-wall junction may affect the thermal bridge (Ψ-value) of the junction at sill, head and jamb, and in turn how this thermal bridge will affect the overall thermal transfer of the building envelope. Surface temperatures will also be investigated in order to examine potential condensation risks. The following investigation of the impacts of thermal bridging offers a contribution to the existing research for the purpose of better defining window-wall interface details for overcladding retrofit.

Scope and Limitations

The study is concerned with the comparative linear thermal transmittance and impact values among the different samples of window-wall connections, and is not focused on finding accurate values in thermal transmittance for the details in the study. Although, from the research conducted, the values in this study seem to lie within reasonable boundaries, due to the simplified nature of the analysis linear thermal transmittance values for the frame connections cannot be assumed accurate to reality.

There was no comprehensive analysis of condensation risk. The methods used only provide a comparison in condensation risk potential.

The detail analysis was carried out to determine what installation strategy carried the best potential to mitigating the thermal bridge at this junction. This was done in the following way:

1. Determine how the variability in design details interface impacts the linear thermal transmittance at the window-wall interface in an over-cladding renovation scenario
2. Calculate the magnitude of influence the thermal bridge heat losses have on the wall assembly's U-value
3. Investigate the potential for increased risk to interior condensation based on interior surface temperature changes for each design scenario

The process of this research demanded a comparison be made on sets of window connection details that are typical specifications for a MURB over-cladding retrofit scenario in Toronto. For this reason, two real-world details were procured as "best" and "worst" detail scenarios for expected thermal bridging potential (one more was extrapolated by the author as an "intermediate" case) for the purpose of modelling in THERM 7.4, in order to see if there is significant impact on the overall U-value of the wall assembly based on the heat loss from the thermal bridge at window-wall interface detail.

It should be reiterated that this study is concerned with the relative linear thermal transmittance values among the different examples and not with finding actual values. As a comparative study, geometrical simplifications in the THERM models were made in that may have affected the accuracy of the numerical results. For example, layers were assumed continuous within the wall structure, and some layers were not included if they were on expected to impact the U-value – for instance air and vapour barriers were excluded. Also, the addition of metal strap anchors at the window perimeter was not included. The author used simplified boundary condition options in THERM, rather than comprehensive ones. Some error is expected and defined within the simulation. There is a 10% limit for energy error norm, which translates to a maximum 1% error in the U-value calculation (LBNL, 2015).

The comparison is meant to investigate differences in thermal transmittance in plausible retrofit details that may occur in a typical MURB retrofit in Toronto. The window-wall interface details in two of the three design options were taken from two projects within the city. Both projects undertook an EIFS overcladding with window replacement, and the window connection details for each differed significantly (See A.1 for actual connection details referenced for this project). The third option is an extrapolation by the author, as a third alternative for comparison.

Boundary Conditions

It should be noted that the entirety of the simulations in this study were carried out using NFRC boundary conditions. Though thermal bridges are commonly evaluated using ISO boundary conditions, for the sake of consistency and simplicity, NFRC conditions were used throughout this study. The use of NFRC boundary conditions for thermal bridge calculation was justified by Barnes et al. (2013) in a similar study:

"Though boundary conditions from ISO Standard 6946 (2007) are a more typical choice, this work attempts to discover any relationship between the window and the window-related psi-value, and since the window U-factor would normally come from NFRC 100 certification, the wall boundary conditions were taken from this standard to keep from having adjacent boundary conditions differ." (Barnes et al, 2013)

Thermal performance of fenestration products is climate dependent, and therefore the boundary conditions used to evaluate fenestration products vary (Hanam et al. 2014). Products are typically developed to perform optimally under the required rating conditions of that climate. The

	U-value		Solar Heat Gain		
	Exterior Temp.	Interior Temp.	Exterior Temp.	Interior Temp.	Solar Radiation
NFRC 100 & 200	-18°C	21°C	32°C	24°C	783 W/m^2
ISO 10077-1, ISO 10077-2, ISO 15099	0°C	20°C	30°C	25°C	500 W/m^2
Passive House Window Certification Criteria	Frame: -10°C IGU: 20°C to -7°C (climate specific)	20°C	30°C	25°C	500 W/m^2

***Figure 12**: Boundary conditions for commonly used in energy calculations. (Hanam et al., 2014)*

ISO boundary conditions use significantly higher exterior temperature than the North American (NFRC) standard; thus, if these conditions are used to evaluate a cold climate scenario, the outcome may be less useful.

Furthermore, the methods which NFRC and ISO use to evaluate center-of-glass (COG), edge-of-glass (edge) and frame U-values differ significantly. For instance, NFRC applies an area-weighted U-value to the COG and a specified perimeter area 65 mm from the edge of frame (as directed by ASHRAE standard), while the ISO standard applies the COG U-value and the linear thermal transmittance (Ψ-value) of the frame-glass edge. Also, ISO guidelines indicate the use of a calibration panel of conductivity 0.035 W/mK in place of the IGU to determine the frame U-value, while the NFRC standard requires the frame to be evaluated with the IGU in place (Hanam et al., 2014).

Furthermore, the thermal zone of influence for the THERM 2-D model is conventionally considered to be 1m (Cappalletti et al, 2011). Thus, this will be used in the following study as the adiabatic boundary condition cut off for the clear wall. 150mm is the length chosen for the visible portion of the glazing.

Boundary conditions for the THERM simulations were set in accordance with NFRC 100 (2010) as follows:

1. Internal opaque surfaces were assigned emissivity based on the material properties indicated in ASHRAE Fundamentals, 2013 (CH. 26).
2. Internal air temperature: 21^{o}C
3. Internal glazing properties are assigned automatically in WINDOW and THERM simulation software

4. Internal frame convection coefficient: 3.12 W/m^{2}K
5. Internal wall surface coefficient: 7.69 W/m^{2}K
6. External air temperature: -18^{o}C
7. External surfaces are assigned a convection coefficient of 26 W/m^{2}K, and radiation is modeled as communication with a black body
8. Adiabatic boundaries are set at the cut-off limits for the THERM model, 1 m from the sill to the extent of the wall, and 366 mm from bottom of frame to top of glazing.

WINDOW 7.4 used the window size, of **W = 1200mm** & **H = 1500mm** as directed by NFRC standards for a fixed lite unit.

Three Design Options

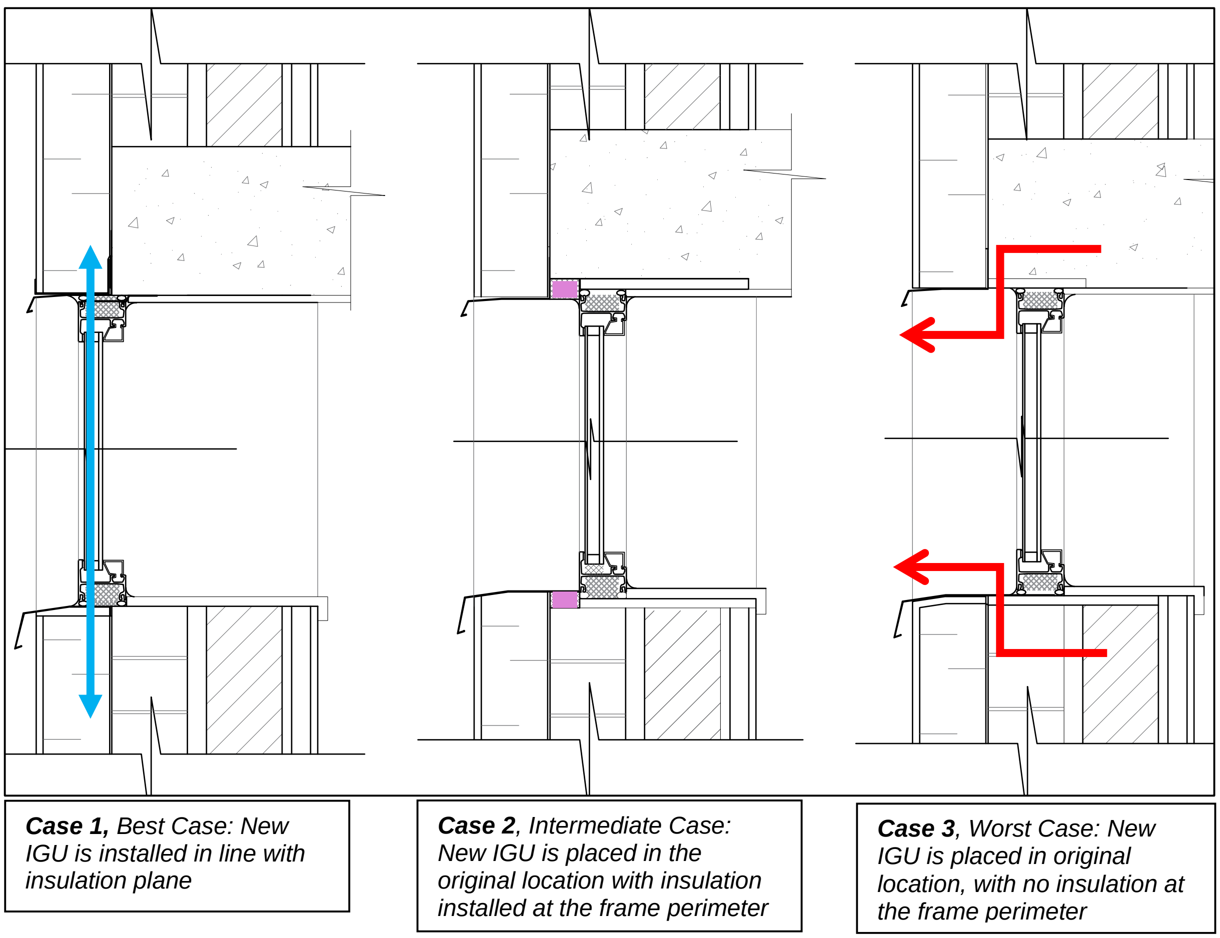


Figure 13*: Sill and Head sections of the 3 scenarios modeled for analysis of installation thermal bridging effects – For all detail sections (Head, Sill, and Jamb) see Appendix 3*

Three scenarios were modeled in THERM for the purpose of comparing their installation thermal bridging effects on U-value. The sections were labelled “Best”, “Intermediate”, and “Worst”. The “Best” case option included the IGU being placed to the exterior of the section, in line with insulation. The “Worst” Case assumed the simplest window replacement option, where the new window was placed in the original location, out of line with the insulation. The “Intermediate” option allowed the IGU to be placed in the original location, but offered an improvement to the “Worst” Case by wrapping insulation into the opening to avoid direct thermal bridging around the perimeter edge of the frame (see Appendix 3 for full section details). The expected performance ranking of the three options is not the key question; as best practice solutions are readily available from a number of sources such as BETA Guide (Morrison Hershfield, 2014) and Tower Renewal Guide (Kesik & Saleff, 2009). The three design options have been labelled with their expected performance ranking. The interest of the study to investigate the magnitude of difference among the various design options. As noted, two typical window installation details were sourced for nominal for this study, though the details created for the study were not exact replicas of the sourced details. Please refer to Appendix 1 see the actual project details. Though best practice guidelines warn against placing the window at an exposed cold bridge such as a floor slab, this may be considered common practice, as was demonstrated to the author during a site visit to an overcladding project (See figure 10).

Establishing a Nominal U-value

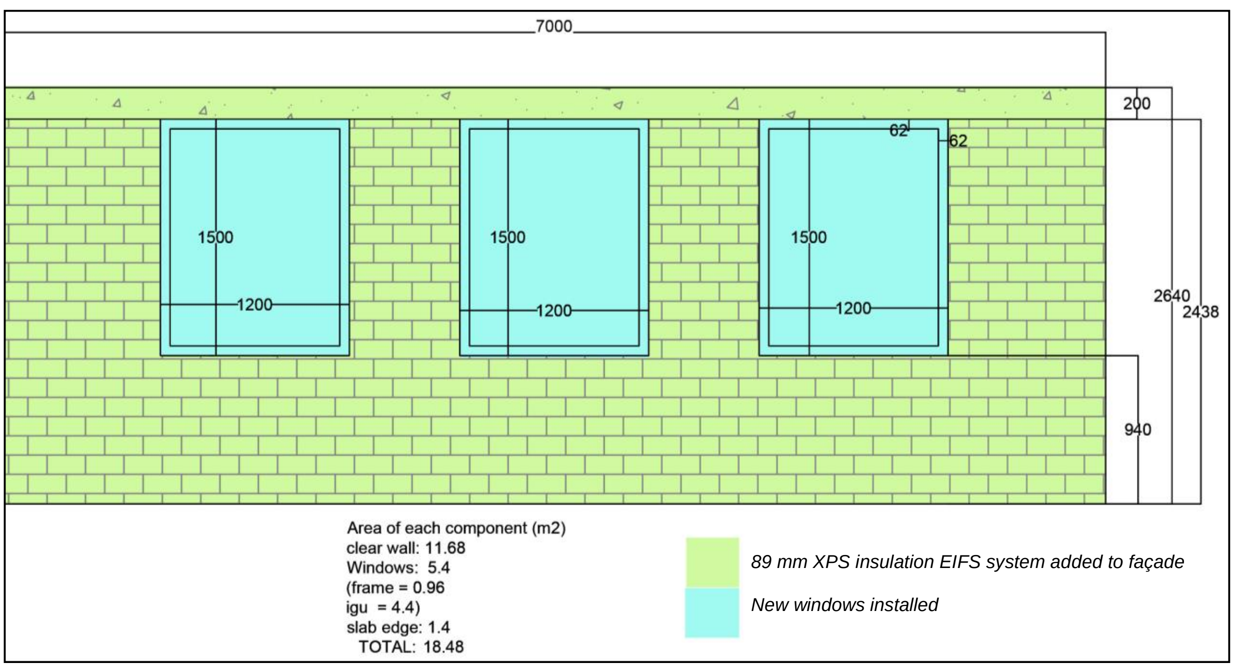


***Figure 14**: Sample wall devised to offer facade component areas in order to compare U_{wall} values*

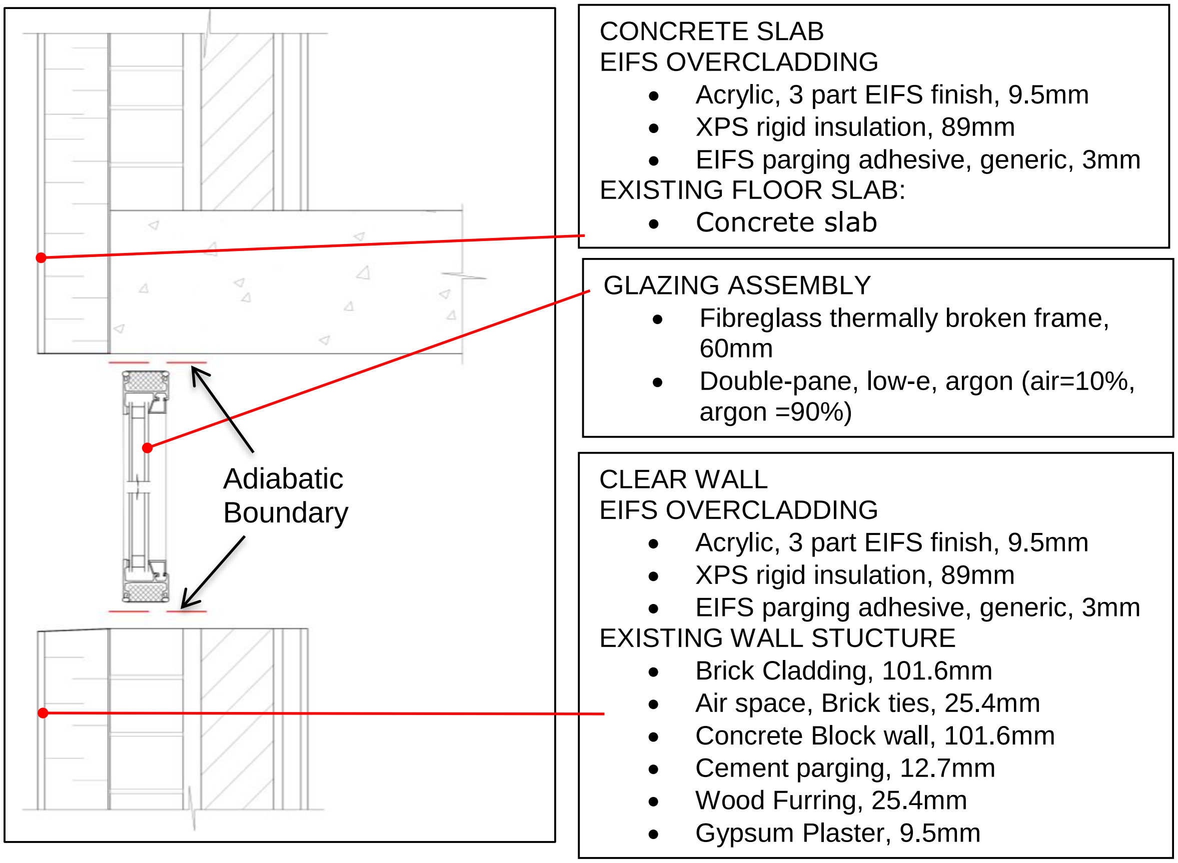


Figure 15: *Wall Section Assembly Area-weighted U-value = 0.64 W/M^{2}K*

For the purpose of establishing an area-weighted nominal U-value to which the subsequent U_{2D} values will be compared, a sample wall was modelled after the typical MURB assembly (as in **Figure 2**). Also, 89mm XPS EIFS insulation, and a new window installation were incorporated as a “typical” overcladding measure.

Table 2*: Conductivity of materials used in wall assembly*

MATERIAL	CONDUCTIVITY (W/mK)
Acrylic 3-part Stucco	0.2
XPS Rigid Insulation	0.03
EIFS Parging Adhesive	0.25
Brick, Common	0.9
Concrete Block	1.5
Cement Parging	0.72
Gypsum Plaster	0.38
Concrete, Poured	1.9

This nominal U-value was established using a simple 1-D area-weighted method. This façade layout was then used in subsequent U-value calculations with the 2-D thermal bridge of each detail incorporated. This method allowed for the comparison of two scenarios:

1. How does including the Ψ-value impact the wall's U-value
2. How do the details compare in their respective impacts to the wall's U-value

To establish a nominal U-value, the area-weighted U-value was then calculated for the sample retrofit wall using the following equation:

$$U_{nominal} = \Sigma\, U_{component} * (A_{component} / A_{total}) \quad \textbf{(1)}$$

The sample wall was simplified for testing purposes, and is not a representation of an actual MURB wall façade. In order to estimate how the linear thermal transmittance of the window-wall interface impacts the overall thermal transmittance of a wall. A generic window size of **1200mm by 1500mm** was used, as this is the standardized test size indicated by NFRC 100 guidelines for a fixed lite window unit.

***Table 3**: Wall Facade Component Areas*

Façade Component	Area (m^2)
Clear Wall	11.68
Windows (3)	5.4
Frame	0.9
IGU	4.5
Slab Edge	1.4
TOTAL	18.48

The study was limited to investigating the impact of the connection details. Thus, the specifications for the fenestration and wall assemblies remained constant. The window product chosen was Inline 700 series frame with a fixed lite, double-pane, 10%/90% air/argon-filled IGU. The frame profile is uniform throughout the perimeter of the window unit. The THERM model was simulated with a simplified warm-edge spacer element and a 150mm glazing insert. Boundary conditions were based on NFRC 100 standard. The U-value for the window assembly were as follows:

U_{frame} = **1.49 W/m^{2}K**;

U_{edge} = **2.01 W/m^{2}K**

The frame and IGU were first modeled in THERM to match the manufacturer's specifications. The window was then simulated WINDOW 7.4; the window performance based in the WINDOW 7.4 simulation was: U_{COG} = **1.44 W/m^{2}K**

OVERALL U_{window} = **1.54 W/m^{2}K**.

This fenestration unit was used for each thermal calculation to compare the influence of the installation detail.

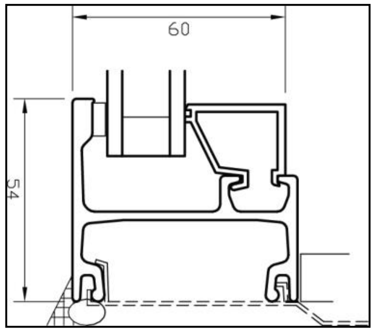


Figure 16: *Inline Fibreglass 700 series fixed lite frame profile. inlinefiberglass.com*

The Calculation Method

The header, sill and jamb detail sections were modelled in THERM 7.4 and WINDOW 7.4 in order to carry out heat transfer calculations. THERM is a graphical 2-dimensional finite element program that calculates conduction heat transfer, developed by Lawrence Berkeley National Laboratory (LBNL), California. The software provides a graphical interface to produce geometrical representation of the given sectional details. The IGU was specified in WINDOW 7.4 for use for the frame and edge U-value simulation in the THERM interface. WINDOW uses NFRC boundary condition guidelines to calculate the glazing performance metrics.

The Thermal Bridging heat flow (W/mK) was calculated using the following steps, similar to those used by Barnes et al., 2013:

1. Simulated the frame sill, jambs, and header details alone in THERM 7.4 with 150mm of glazing to obtain the U_{window} used for the L_{2D} calculations
2. Simulated two, 1m wall sections (one includes the floor slab edge), not including connection and flashing details, in THERM 7.4 to obtain $U_{headerwall}$ and $U_{clearwall}$ used for the L_{2D} calculations. $U_{clearwall}$ is used for sill and jamb connections, while $U_{headerwall}$ was used for the header detail connection
3. The assemblies with window, framing, and wall were each simulated in THERM 7.4, including flashing and connection details to obtain the thermal coupling coefficient, L_{2D}.
4. Solved for ψ-value for each detail: sill, jambs, and header, using the following equation:

$$\Psi = L_{2D} - \sum_i U_i * L_i \qquad (W/mK) \qquad \textbf{(2)}$$

$$\text{Where: } L_{2D} = \sum U_{install} * L_{install} \qquad (W/mK)$$

L_{2D} = Linear thermal transmittance of the full detail, considering installation effects (generated from THERM), and uses the install height (see figure 18) in its calculation
U_i = U-value of the isolated components (generated in THERM)

$\mathbf{L_i}$ = length applied to the isolated wall and window geometrical models simulated in THERM
$\mathbf{U_{install}}$ = the 1-dimensional thermal transmittance of the installed situation separating the exterior and interior environments. As calculated in THERM
$\mathbf{L_{install}}$ = full length (or height) of the installed situation, as modeled in THERM

5. Once the ψ-values were calculated for each detail, the effective U-value for a single window with dimensions W=1.2m; H=1.5m **(A_{window}=1.8m²)** was calculated using the following equation (source: Cappalletti et al., 2011):

$$U_{2D}=\frac{U_{window}*A_{window}+\Psi_{sill}*W+\Psi_{jambL}*H+\Psi_{jambR}*H+\Psi_{head}*W}{A_{window}} \quad (W/m^2K) \qquad \textbf{(3)}$$

6. The relative change in U-value, with installation Ψ-value included, was then calculated for each installation scenario using the following equation:

$$\Delta U_{window}=\frac{U_{2D}-U_{window}}{U_{window}}*100 \qquad (\%) \qquad \textbf{(4)}$$

Sill Anchor Placement:

The offset of the Best Case frame from wall structure required that structural support anchors be installed at 600mm spacing along the windowsill to tie in the unit. The following diagram, Figure 15, shows the placement of the anchor straps, as well as the method for calculating the additional thermal bridge created by the anchors

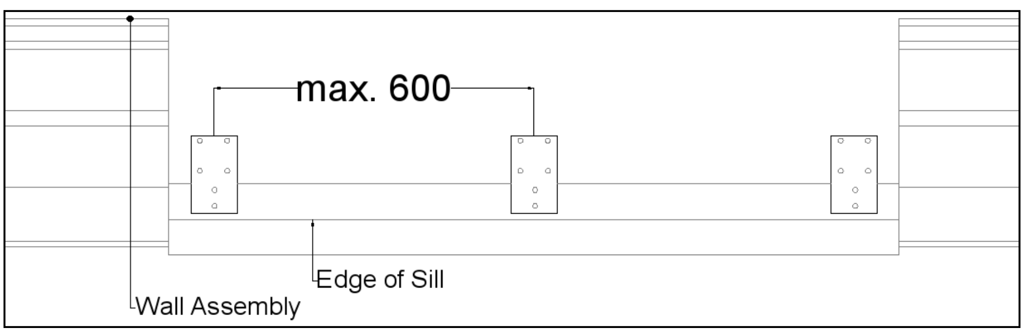


__Figure 17__: structural anchor placement at the "Best" Case sill. For the purpose of evaluating the average Ψ-value at the sill

The structural steel anchors were modeled for the "Best" Case sill only, and the average Ψ-value was assigned to the "Best" Case sill using the following equation:

$$\Psi_{sill}=0.19(\Psi_{sillanchored})+0.81(\Psi_{sillclear}) \qquad (W/mK) \qquad \textbf{(5)}$$

Results and Discussion

A nominal 1-D U-value was established for the retrofit wall. This was done using equation (1) to attain a simple area-weighted U-value. Each element, the clear wall, window, and the wall including slab edge, were independently simulated in THERM to establish their isolated U-values. These values were used to calculate the nominal value of the wall. This nominal U-value was then used to compare the resulting U_{2D} for the three installation options. U_{2D} refers to the resulting U-value once linear thermal transmittance from the Ψ-value is incorporated. Practically speaking, the Ψ-value can be attributed to the wall or the window U-value to attain a U_{2D}. For this study the U_{2D} was attributed to the U_{window}.

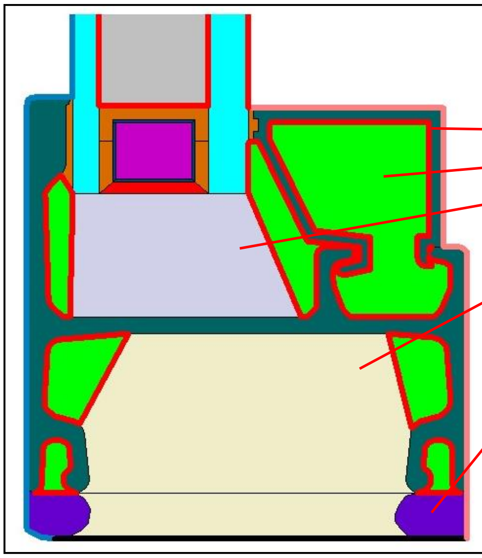
The area-weighted U-value for the nominal wall was calculated to be **0.64 W/m²K**.

Table 4*: Area-weighted U-value of the nominal wall assembly, which does not consider thermal bridging effects.*

Assembly Component	Area (m^2)	% Area	Thickness (mm)	U-value (W/m^2K)
Clear Wall	11.68	63%	377.7	0.26
Windows (3)	5.4	29%	--	1.54
Slab Edge	1.4	8%	101.5	0.3
TOTAL	18.48	--	--	**0.64**

Figure 15 shows the components of the wall assembly simulated in the study. The wall section is a generic representation of the assembly, whereby the connection detail linear thermal transmittance is not calculated in the performance evaluation of the wall. Below are the material properties assigned within the THERM model.

The window frame diagram was sourced from a proprietary website (inlinefibreglass.com) and appropriated for use in the study. Figure 18 is the author's interpretation of the frame detail, created from a profile diagram. An effort was made to model the frame to have a similar U-value to the product specifications. Below is the frame section, as modeled in THERM.



Material	Conductivity (W/mK)
Fiberglass	0.231
Frame Cavity	0.0592 (k.eff)
EPS	0.038
Low density Polyurethane foam	0.024
Backer Rod	0.06
Spacer	
Silica Desiccant	0.03
Polyisobutylene	0.2
Polysulphide	0.4
Aluminum	160

***Figure 18**: Inline Fiberglass frame modelled in THERM with Material conductivities*

Three window installation scenarios were tested (**Figure 13**). Each head, jamb, and sill installation detail was simulated in THERM 7.4, and Ψ-values were calculated using equation (2):

$$\Psi = L_{2D} - \sum_i U_i * L_i \quad (W/mK)$$

Where:

L_{2D} = Linear thermal transmittance of the full detail, considering installation effects

U_i = U-value of the isolated components (generated in THERM)

L_i = length applied to the isolated wall and window geometrical models simulated in THERM

The lengths simulated in THERM were determined by conventions in the literature. The author chose to 1000mm length of clear wall with 150mm glazing (**Figure 19**). These lengths were chosen to ensure a natural adiabatic condition was reached at the extremities of the simulated model.

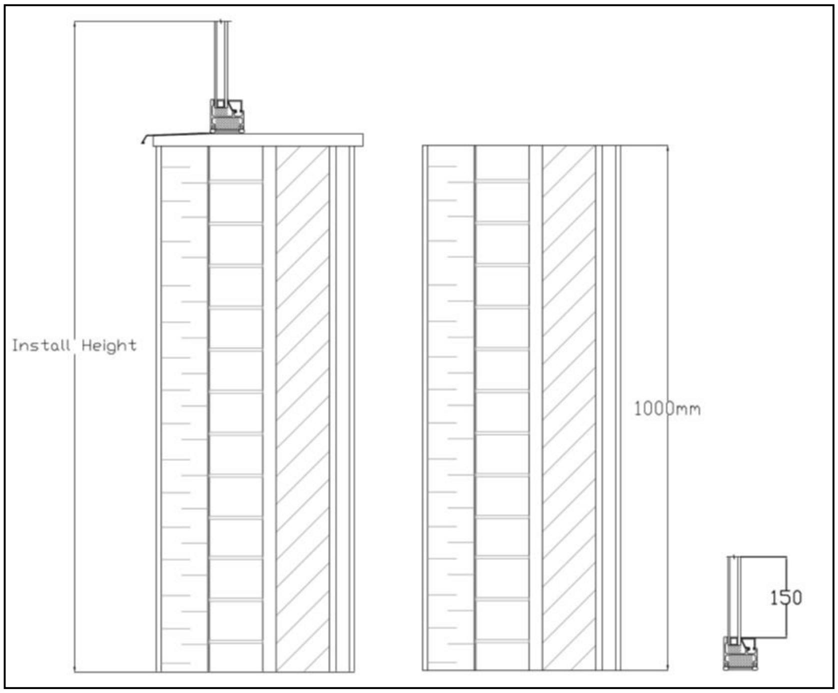


***Figure 19**: Geometry of THERM models. Head and Jamb were modeled with like geometry*

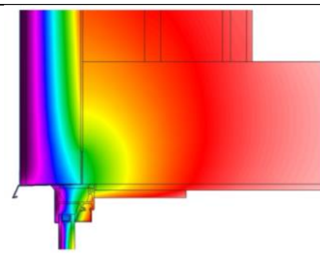
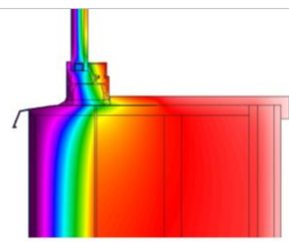
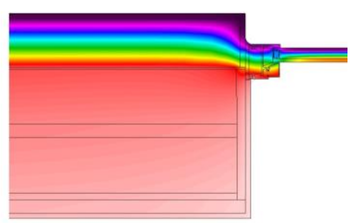
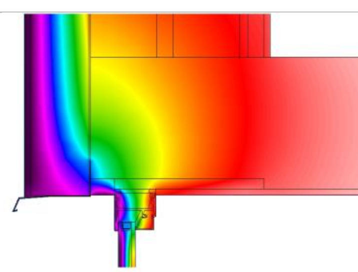
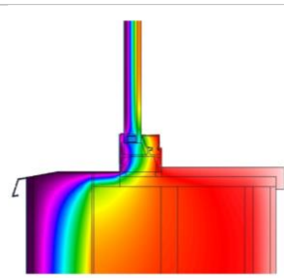
Linear Thermal Transmittance Results

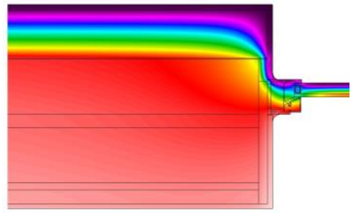
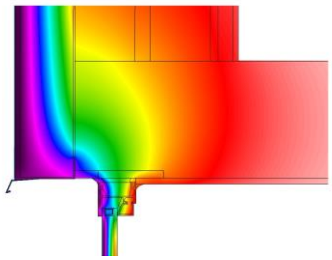
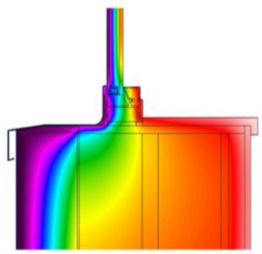
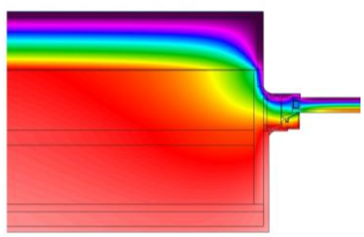
It has been established through the literature that taking into consideration linear thermal transmittance has substantial influence on the true thermal losses through the building envelope. The three design options were modelled to quantify these losses at the window-wall interface. The Ψ-values generated were then used to calculate the effective U-value of a sample wall. This process was chosen to illustrate the magnitude of impact that linear thermal transmittance has on the overall thermal losses of the building envelope. The following discussion describes these findings, compares variance in linear thermal losses among the three design options, and proposes a means to use the calculation method to assess design modifications and comparisons.

As can be observed from the overall Ψ-values generated, it was found that the scenarios were ranked as expected, for “Best” to “Worst”. However, some discrepancies did appear from the modelled details. The “Best” Case jamb details had no discernable thermal bridge. The reason for this may be due to the relative simplicity of the detail. The negative value of -0.001 W/mK for the “Best” Case jamb detail may be a demonstration of the simplified boundary conditions used throughout the study as well. Though negative values can the case in super0insulated sceanarios, it is not realistic in this case. Thus, the value of 0.0 W/mK is attributed to this detail.

In further observation of the resulting Ψ-values, it was found that the “Intermediate” Case header detail had noticeably lesser thermal bridging than either of the other Cases. This inconsistency is discussed further in the next section.

Table 5: *Ψ-Values for "Best", "Worst" and "Intermediate" case details*

Case	Component	Color Isotherm	Ψ-value (W/mK)
BEST CASE	Head		0.479
	Sill		0.050
	Jamb		-0.001
INTERMEDIATE CASE	Head		0.477
	Sill		0.111
	Component	**Color Isotherm**	**Ψ-value (W/mK)**

	Jamb		0.140
WORST CASE	Head		0.589
	Sill		0.240
	Jamb		0.254

Even though the “Intermediate” case was, overall, lower performing than the “Best” Case, the **Ψ-value** for the “Intermediate” header detail in particular is somewhat better than the other two details. Whereas the “Best” case header Ψ-value was **0.479 W/mK,** and the “Worst” case header Ψ-value **was 0.589 W/mK**, the “Intermediate” case was **0.477 W/mK**. This is likely due to the flashing detail, which was placed in contact with the concrete slab. The “Intermediate” Case having insulation at the perimeter had the least contact between the aluminum and concrete, this resulting in a relatively low Ψ-value. The assigned material for the flashing was highly conductive, and this allowed a considerable thermal path at the slab edge.

To demonstrate the isolated impact of this detail in particular: If the "Worst" case header detail were improved by wrapping insulation into the frame opening, just at the header, and the Ψ-value$_{header}$ could be reduced from **0.589 W/mK** to **0.477 W/mK**.

Comparing the Ψ-values to similar results within the literature

The current study was examined with respect to a similar study by Cappalletti et al. (2013). It can be noted that, for the most part, the values are comparable, which suggests the Ψ-values generated in this study are within a reasonable range. However, the header details in the current study show a considerable discrepancy with the comparative study, as can be seen in **Table 6** below. This discrepancy is due to a specific detail decision made in the current study that created a significant thermal bridge along the slab edge. This is discussed further in the next section.

***Table 6**: Comparing Psi-values of current study to similar (Cappalletti et al, 2013)*

Configuration	Placement	Current Study (W/mK)	Cappalletti et al. (W/mK)
Interior, uninsulated frame (WORST CASE)	Head	0.589	0.229
	Sill	0.254	0.242
	Jamb	0.240	0.221
Intermediate, insulated frame (INTERM. CASE)	Head	0.477	0.098
	Sill	0.111	0.179
	Jamb	0.140	0.152
Exterior Placement (BEST CASE)	Head	0.479	0.398
	Sill	0.050	0.059
	Jamb	0.00	0.055

Evaluating the Impact on U_{2D} and the Wall's U-value

Equation (3) was used to determine the U_{2D} of the window, taking into consideration the Ψ-values above (**Table 5**). The results indicate that window placement within the frame does have significant impact on the window U-value (U_{2D}). Incorporating the Psi-value dramatically increases the window's performance. It is very useful to note, however, that improving details from "Worst" case, which have increased thermal losses of 30.9% from the nominal, to "Best" case details will improve the wall's performance by as much as 17%.

Table 7: *Window's effective U-value (U_{2D}) due to thermal bridging at the window-wall interface*

			Comparison to similar study (Cappalletti et al, 2013)
NOMINAL (does not consider Ψ-value): **U_W = 1.54 W/m^{2}K**			**U_W = 1.45 W/m^{2}K**
CASE	**U_{2D} (W/m^{2}K)**	**Change in the Window U-value from nominal (%)**	**Change in the Window U-value from nominal (%)**
BEST CASE	**1.89**	22.8	8.9
INTERMEDIATE CASE	**2.17**	40.6	12.7
WORST CASE	**2.52**	63.4	46.2

Table 8: *Effective U-value of the wall due to Ψ-value impacts of each design detail*

CASE	**U-value of the wall (W/m^{2}K)**	**change in wall's U-value (%)**
NOMINAL (does not consider Ψ-value)	0.64	--
BEST CASE	**0.74**	13.8%
INTERMEDIATE CASE	**0.85**	24.6%
WORST CASE	**0.92**	30.9%

Using 2-D Thermal Analysis to Improve Details

Below depicts the design deficiency of the header detail, and potential improvement on the Ψ-value and consequent impact on the U_{2D}.

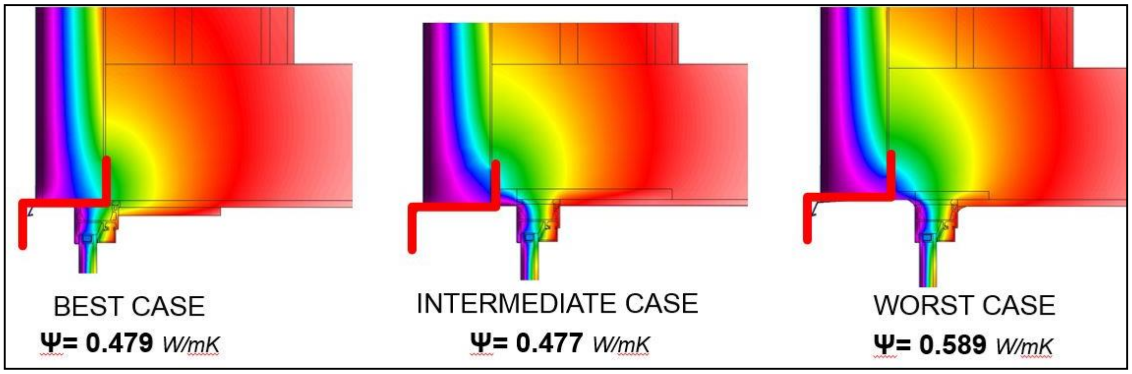


Figure 20: *Current **Ψ-value** of the header detail with the assigned aluminum flashing (k=160 W/mK)*

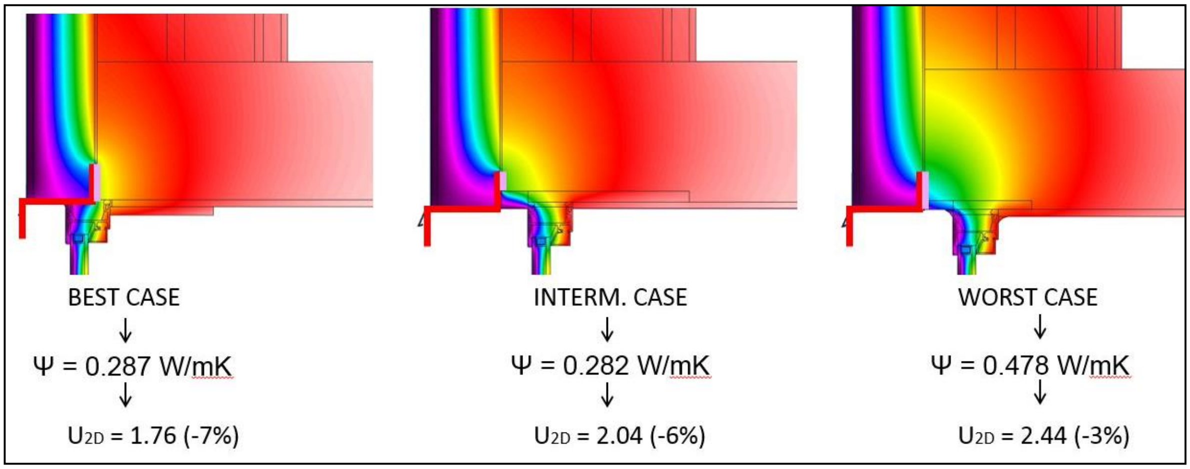


***Figure 21**: The reduction in **Ψ-value** and subsequent effective U-value (U_{2D}) of the window with insulation between flashing and concrete edge. Reduction % are with respect to initial U_{2D} calculation (**Table 7**)*

It is useful to designers and architects to understand how these values fit into the building envelope heat loss metric. This would have an overall impact on the U_{2D} Furthermore, if the flashing detail were improved by placing insulation between the concrete edge and the aluminum flashing, as proposed in Figure 20, the linear thermal transmittance at the header can be reduced further to **0.282 W/mK**. By improving the header thermal bridge by about **50%**, the U_{2D} of the window would be reduced from **2.52 W/m²K** to **2.31 W/m²K**, effectively reducing the overall wall's U-value from **0.92 W/m²K** to **0.86 W/m²K.** Therefore, it can be seen by using 2D thermal modelling that the primary deficiency of the "Worst" Case window detailing was the header, and improving the header detail brings the thermal performance of the wall similar to the "Intermediate" Case. This type of assessment can by useful to evaluate different strategies in detail improvements before making major design changes such as moving the window outboard of the structure like in the "Best" Case. This process demonstrates how the calculation method proposed may be useful to assess thermal transmittance impacts through detail modifications.

Utilizing 2D thermal analysis offers a more accurate analysis of building envelope performance. This is often neglected, as there is little incentive for designers to incorporate linear thermal losses in their U-value calculations. Yet Morrison Hershfield (BETA Guide, 2014) assert, quantifying and mitigating thermal bridging can offer payoffs when comparing the improvement of detail changes to the improvement of a product. For example, replacing the double glazed IGU with triple glazing will offer a product with significantly lower U-value. However, the performance of this product may be undermined if the interface is not well detailed. Table 9 demonstrates this comparison. Using the current study's nominal baseline, it can be shown that the triple-glazing option seems substantially better than double-glazing, if the thermal bridging is not considered. However, not taking into consideration the importance of the detail connection, and thus neglecting to choose the best detail option will undermine the performance of the assembly.

Table 9*: Comparing effective U-value impacts of detail improvements to product improvements and % increase from Nominal wall U-value of 0.64 W/m²K*

	"Worst" Case	Nominal Wall /w Triple Glazing	Triple Glazing /w "Worst" Case Ψ-value losses	"Best" Case	Triple Glazing /w "Best" Case Ψ-value losses
U_{window}(W/m²K)	2.52	1.1[1]	1.79[2]	1.89	1.35[3]
U_{wall} (W/m²K)	0.92	0.50	0.71	0.74	0.58
Percent Increase (%) from Nominal U_{wall}	31%	-14%	10%	14%	-9%

As a 1-D analysis, it appears that the triple-glazing option is a substantial improvement from double-glazing. But if the detail is poor, the triple glazing "Worst" Case thermal losses (10%) are comparable to the double-glazed option with a good detail which sees 14% thermal losses from the nominal.

As Berggren et al (2013) ascertain, designers and architects need to have a good interpretation of what thermal bridging impacts actually mean in relation to an energy efficient design. Their research, which interviewed a number of engineers and architects in a European setting, found that the general understanding of energy calculations was good. However, in a North American setting, thermal bridging analysis is not typical (Morrison Hershfield, 2014). Thus, clarifying how a thermal bridging metric translates to a U-value metric is useful for general application in the design world.

The BETA guide (2014) indicates that decreasing the window-installation linear thermal transmittance by approximately 40% on a building with 40% glazing, can effectively improve the U-value by up to 18%. In the same line, with the sample wall used in this study with 30% WWR, it was found that ignoring the installation linear thermal bridge overlooked a significant amount of heat loss, whereby the Best case increased the U_{window} from the Base case by almost **23%,** from **1.54 W/m²K (Base) to 1.89 W/m²K (Best),** which had an overall effect on the Wall U-value of **13.8%,** increasing U_{wall} **from 0.64 W.m²K to 0.74 W.m²K**. In conclusion, this study supports

[1] From manufacturer spec. inlinefibreglass.com
[2] Calculated using the same Ψ-values as "Worst" Case
[3] Calculated using the same Ψ-values as "Best" Case

the assertion that incorporating thermal bridge losses at the window-wall interface is imperative to understanding the true thermal performance of a building envelope.

Internal Surface Temperature Results

The internal surface temperatures were generated for the sill details through the THERM simulation to determine fluctuations due to the changes in installation details. The frame was

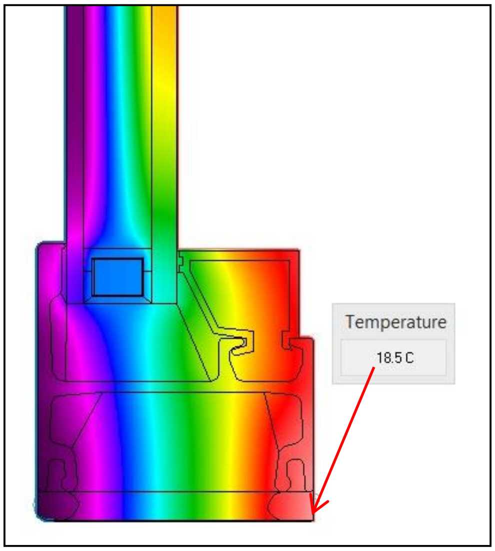


***Figure 22**: THERM simulation of the isolated frame with Adiabatic Boundary at the base*

simulated in isolation, with the adiabatic boundary condition at the base of the frame detail. Results are shown in Figure 22.

The isolated frame displays an internal surface temperature or 18.5°C at the sill edge.

The "Worst" Case sill presented a temperature of 15.7°C, with a difference of 2.8°C from the isolated profile, while the "Intermediate" Case presented a temperature of 16.3°C – a difference of 2.2°C. The "Best" Case presented a temperature of 17.0°C.

Overall, the temperature variance among the three sill details themselves was only 1-1.7°C and was therefore not significant enough to note. Nonetheless, the temperature range between the isolated sill profile and the installation profiles is notable, as a difference of 3°C can impact condensation risk. This conclusion is in line with similar studies of Totten (2008) and O'Brien (2005).

The "Best" case scenario, Figures 23-24 show the interior surface temperature at the sill is notably lower at the anchor locations. The significant impact on the surface temperature occurs when a sill in supported structurally with metal anchors (**Figure 24**).

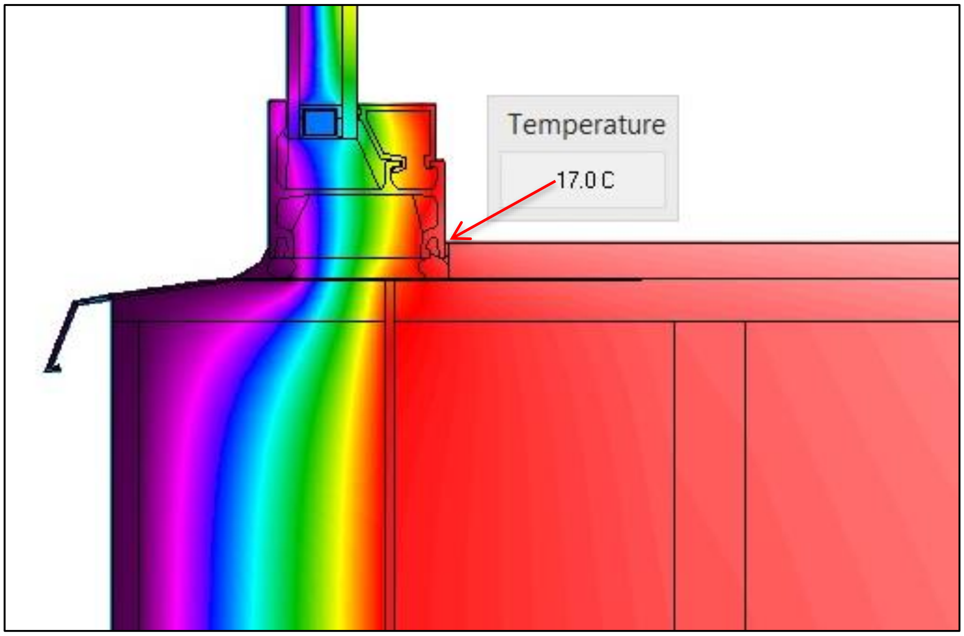


Figure 23*: Best Case sill temperature profile. Temperature at sill edge = 17.0 deg.C*

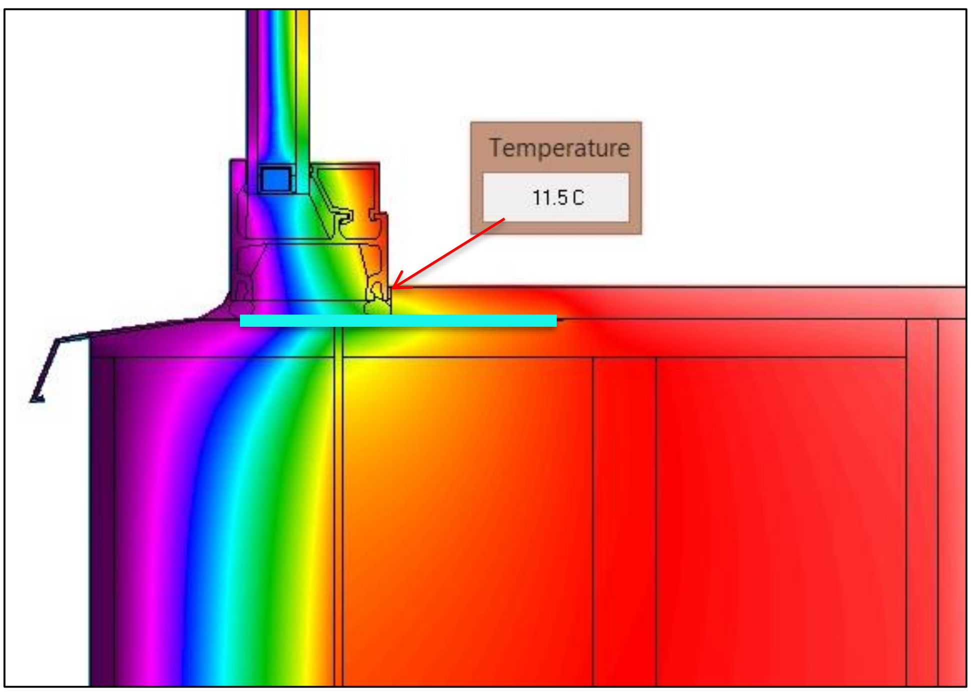


Figure 24*: "Best" Case sill with steel anchor temperature profile. Temperature at sill edge = 11.5 deg.C*

The surface temperature at the anchored locations is 11.5°C, demonstrating a temperature difference of 7 degrees. Though the intermittent anchor ties do not deplete the Ψ value greatly, these isolated cold bridges may impact condensation potential.

Improving the Sill Detail to increase surface temperatures

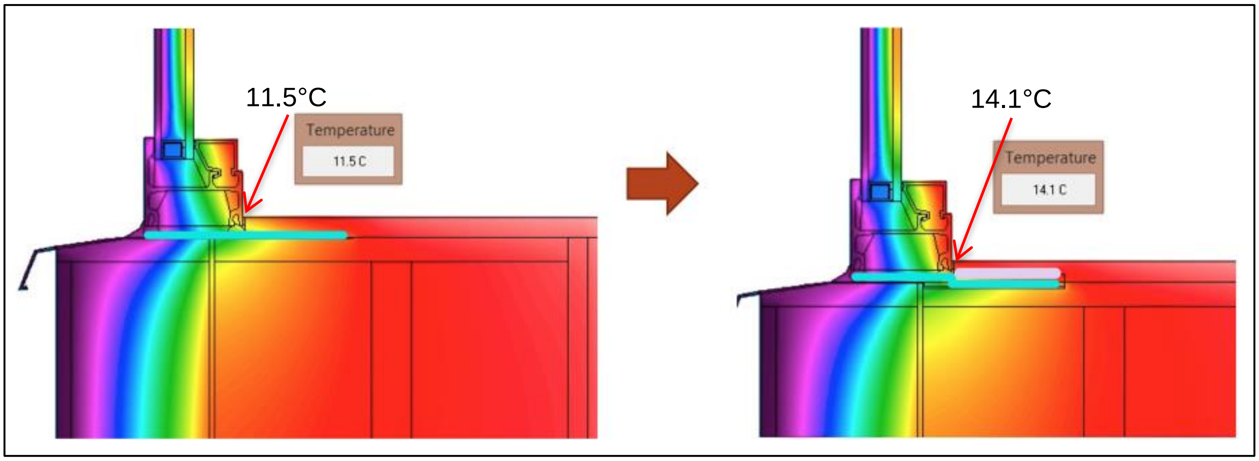


***Figure 25**: Potential temperature profile change due to detail improvements at sill*

If the profile of the anchor can be modified to accommodate insulation around the edge, this could mitigate the cold surface effect.

In order to avoid mould risk, it is good practice to ensure surface temperatures do not fall below 15°C for prolonged periods of time (assuming 50% R.H) (Sierra et al., 2015). Though the THERM models have not been built for absolute accuracy, a difference in temperature profile of 7°C from the isolated frame profile outlines the impact of detail connection and specifically the presence of structural anchors running parallel to the heat flow.

Conclusions

This paper aimed to investigate the impact of typical window installation options on energy use in an EIFS overcladding scenario. The goal was to investigate the four key window interfaces – sill, jambs, and head – of three typical window installation options for a full window assessment of thermal bridging impacts at the window-wall connection. Through this learning process, the aim was to work towards a viable and straightforward method can be applied for retrofit design situations in order to better assess design decisions and their impacts on thermal bridging at the window-wall interface.

It was found that a typical window installation detail does add significant thermal losses, if assessed with 2D thermal modelling, and thus linear thermal transmittance should be considered at the window-wall interface. Furthermore, variation among the detailing options did result in significant variation in linear thermal losses, thus careful attention to this detail interface should be paid in order to mitigate unnecessary heat loss.

The investigation of three window installation options was carried out. The "Best" case, modelled after the Green Phoenix window-wall detail design provided by Hilditch Architects, was found, as expected, to be the best performing detail in terms of thermal bridging energy losses. However, it would be useful in a retrofit scenario to understand what alternatives could be considered, as limitations in budget or scheduling may limit design options. As expected, the optimal window placement proved to be the external position, with the IGU in line with insulation, as demonstrated in the guides and literature (Misiopecki et al, 2013, Cappalletti et al, 2011, Morrison Hershfield, 2014). Detail variation showed to have effect on the overall thermal losses of the wall assembly. Compared to the nominal wall, incorporating the thermal bridging of the "Best" Case decreased the wall's U-value by 13.8%, and in the poorly designed detail, as in the "Worst" Case, the U-value was increased by 30.9%.

As for temperature profile changes, only the sill detail was examined. Though variance among the details did seem to have great impact on the internal surface temperature at the sill, it was found that conductive anchoring running in line with the heat flow might have a detrimental effect on the surface condensation potential. This issue, however is one that presents as a 3-dimensional heat flow problem, and would required more careful analysis.

Further Research

Considering the complexity of the window-wall interface detail, this junction can be analyzed a number of ways, as additional data is crucial to getting a clear portrait of how this detail may be best approached by designers. This comparison study was not carried out in a manner that defines singular construction changes.

1. The detail studies should be investigated with further scrutiny in a comprehensive manner to understand better optimal solutions to reduce thermal bridging at the window frame.
2. Future work should include investigating a range of wall typologies, including walls with interstitial or interior insulations.
3. The details could also be investigated for condensation risk in more detail, perhaps coupling the models with hygrothermal analysis using real time local climate data to get more precise results.
4. It would also be useful to look at different window sizes, window-wall ratios, and different window configurations in order to get a more comprehensive understanding of the thermal bridge impacts.

Appendix 1 – Reference details used to develop the Best and Worst Case scenarios

Details sourced for Best Case:

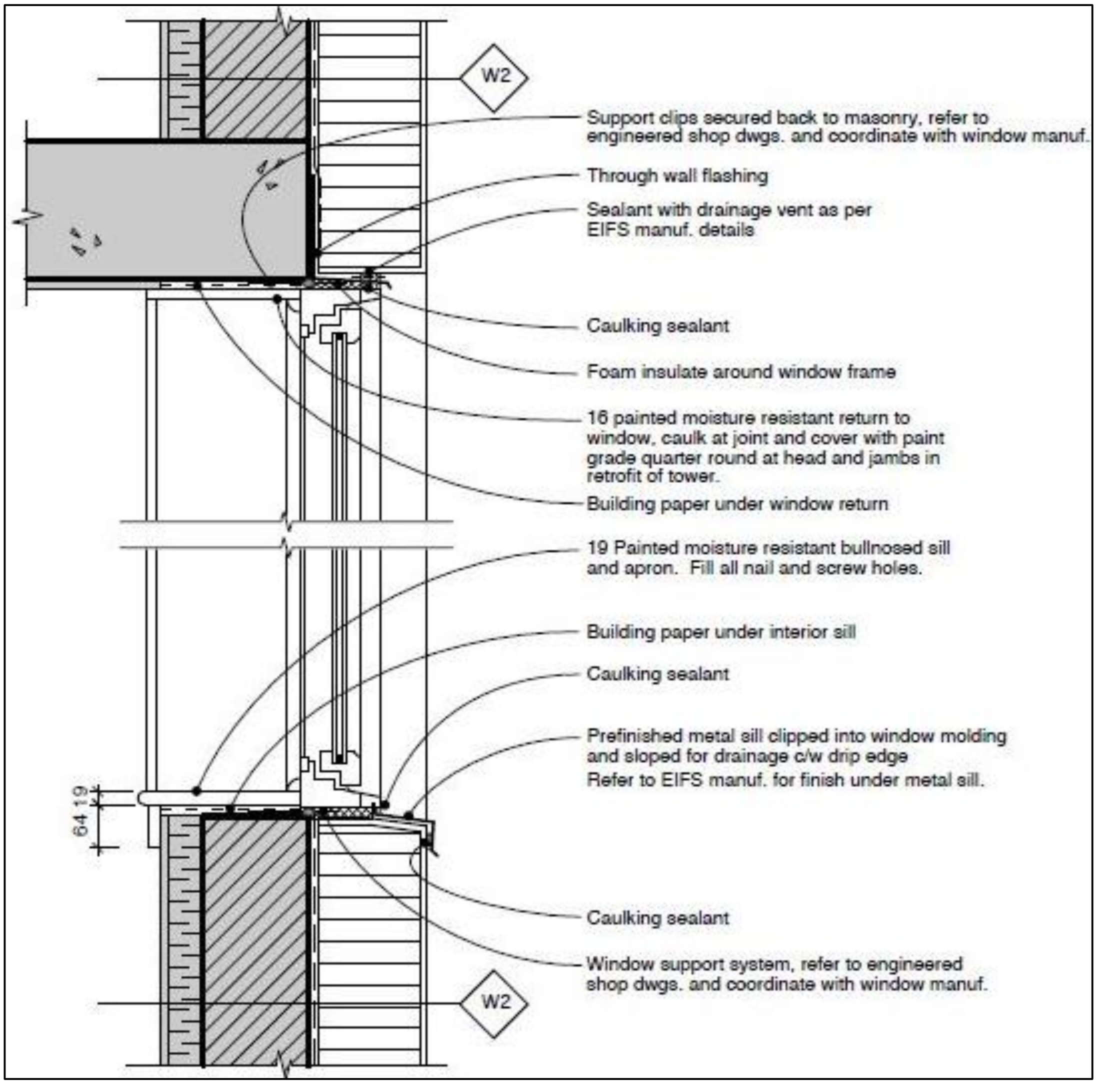
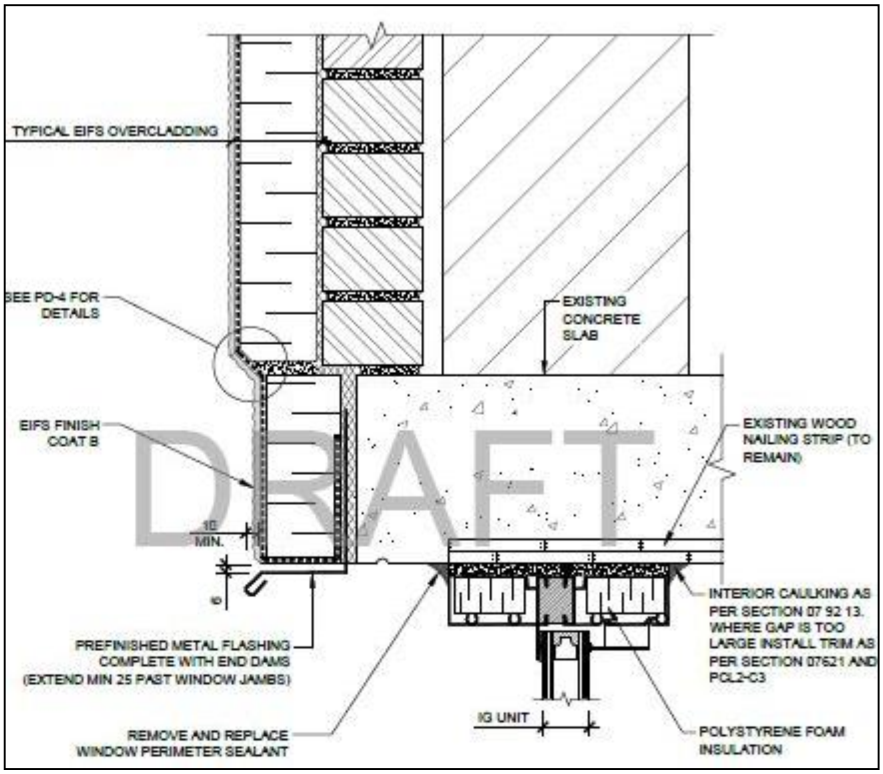
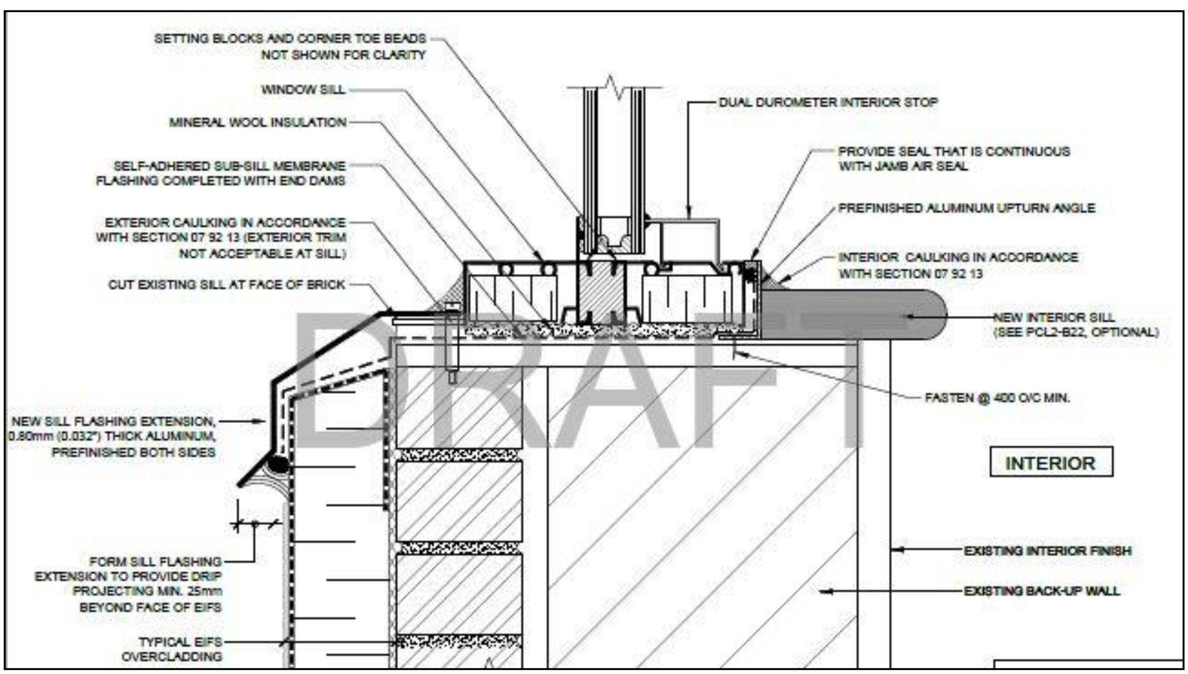


Figure A1.1 *Courtesy of Hilditch Architects & Prof. Vera Straka*

Details sourced for Worst Case:





Figures A1.2*: Courtesy of Park Property Management Inc.*

Appendix 2 – THERM Verification Exercise

The THERM verification exercise was performed to ensure the author's THERM modeling techniques were sufficiently accurate to carry out the research for this project. The author replicated a frame sill model from Misiopecki et al. (2013), and with the information provided in their report, the results the author was able to find was the lowest internal surface temperature at the sill, and this did match. The Ψ-value could not be calculated, because the report did not

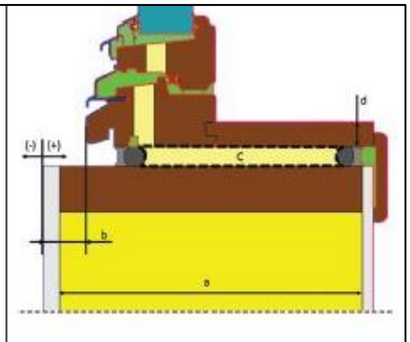
Geometry						
Case Number		1	2	3	4	5
Insulation Thickness a, mm		246	198	296	246	246
Internal Sill/Flashing Thickness d, mm		19	19	19	19	32
Insulation Conductivity C, W/(m·K) (dotted area)		0.032	0.032	0.032	0.02	0.032
Wall U-factor, W/(m²·K)		0.19	0.22	0.15	0.19	0.19
		Linear Thermal Transmittance Ψ, W/(m·K)				
Position in Window Opening b, mm	−42	0.047	0.040	0.052	0.041	0.032
	00	0.019	0.014	0.024	0.015	0.014
	+ 35	0.015	0.012	0.019	0.012	0.011
	+ 85	0.025	0.031	0.026	0.023	0.022
	+ 140	0.041	—	0.032	0.040	0.039
		Lowest Inside Surface Temperature, °C				
in Window ng b, mm	−42	12.5	—	11.3	—	—
	00	13.4	—	13.3	—	—
	+ 35	13.6	—	13.5	—	—

Figure A2.1 *: Reference data used for THERM verification model results* offer the exact assembly lengths used in their THERM model. The detail created by the author was modeled after example (1) in the aforementioned report; please See Fig. A1 for the details of that model.

Material properties were also replicated from this report, and boundary conditions followed NFRC 100 (2010) as indicated in the report replicated.

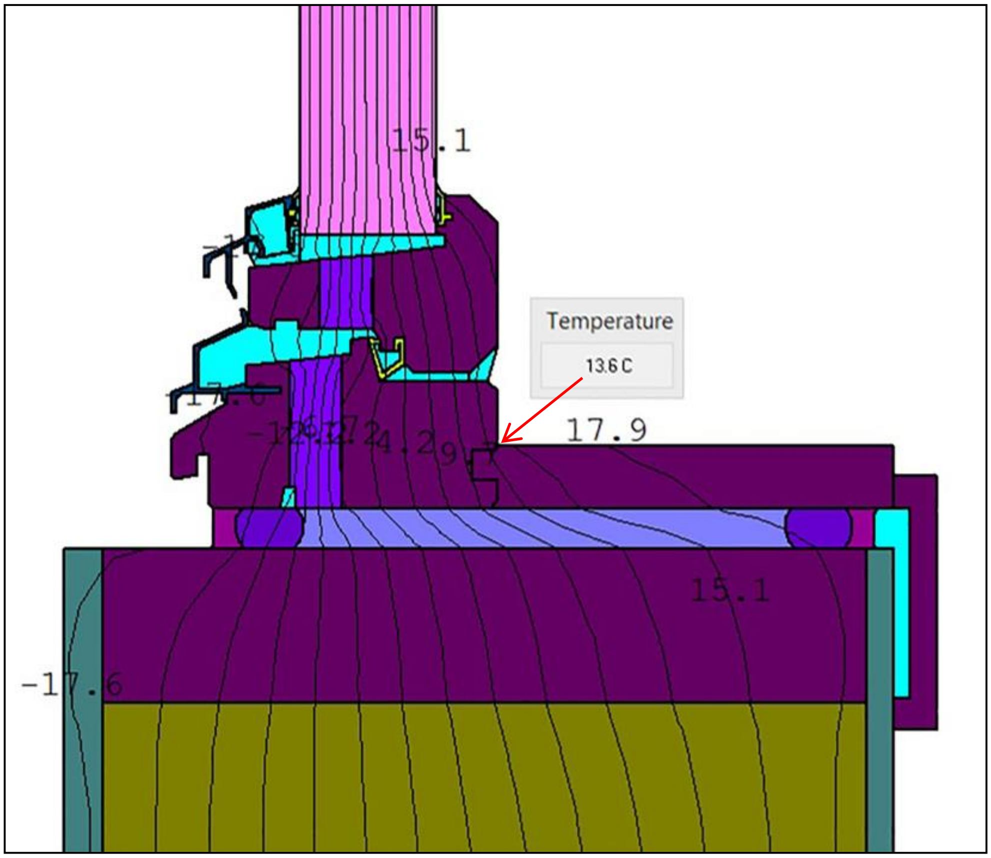


Figure A2.2: *Authors Replicate for verification. Lowest temperature at sill = 13.6 deg.C*

Appendix 3 – Modelled Details

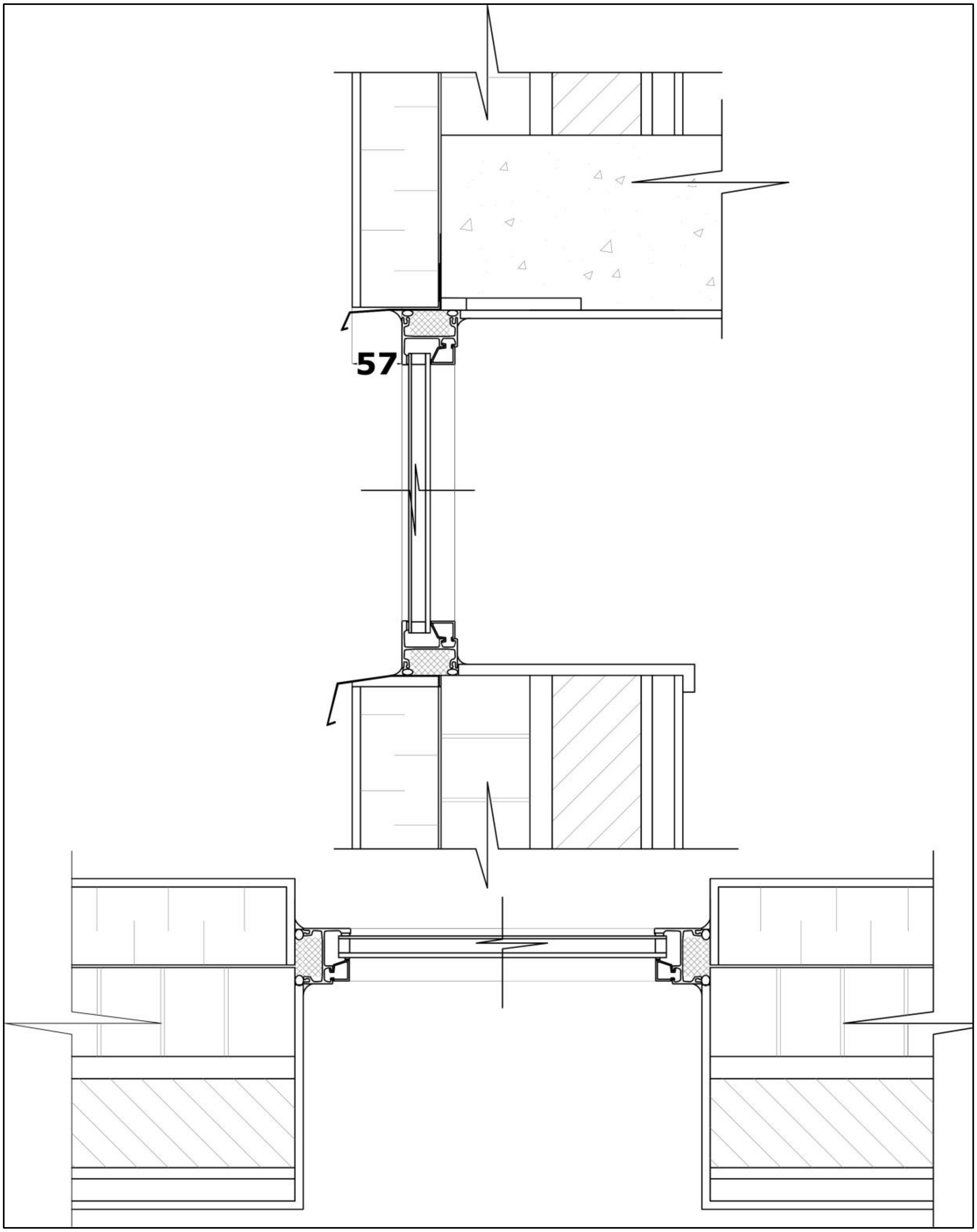


***Figure A3.1**: Best Case details modelled in THERM*

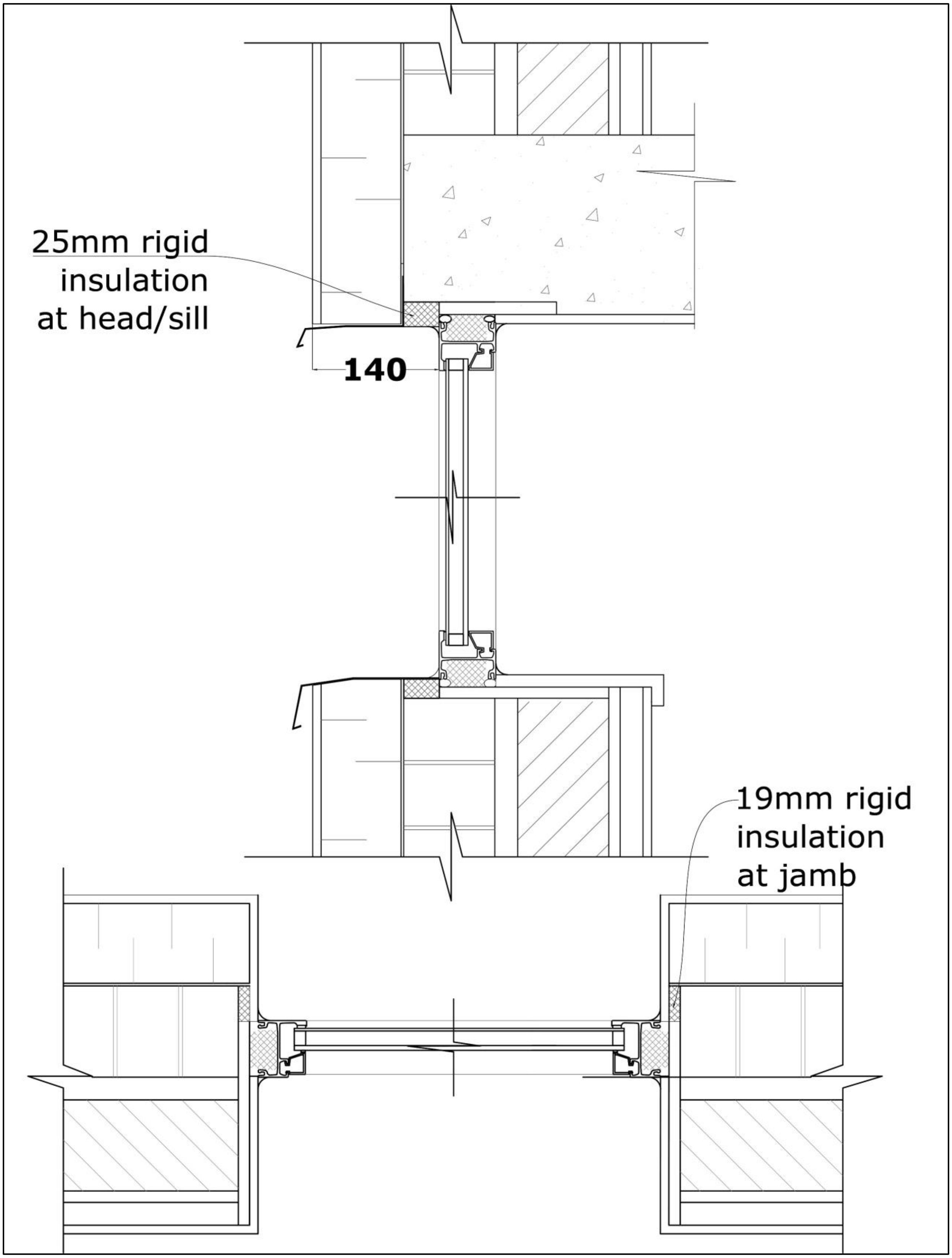


Figure A3.2: *Intermediate Case details modelled in THERM*

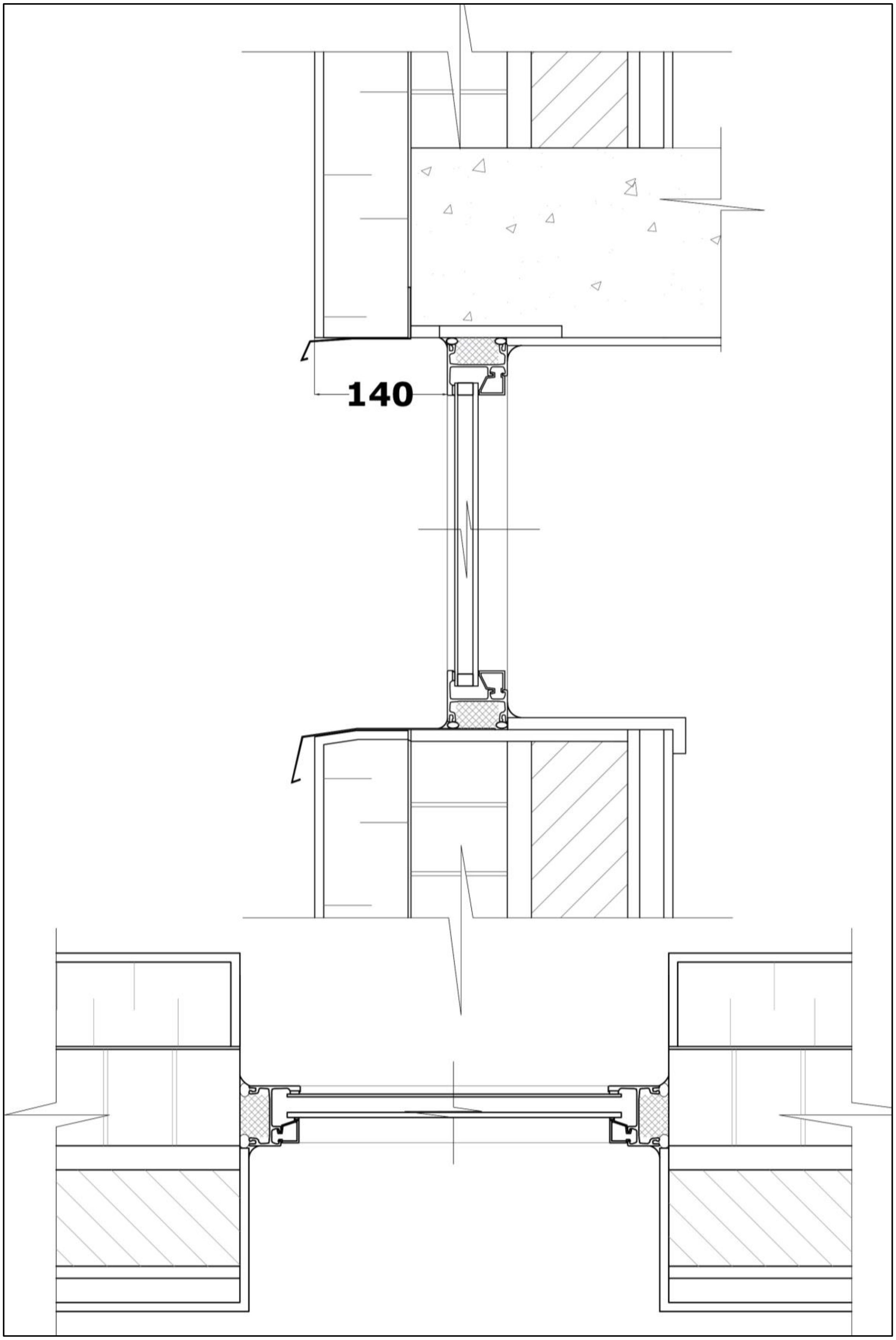


***Figure A3.3**: Worst Case details modelled in THERM*

References

Ascione, F., Bianco, N., De Masi, R., de Rossi, F., & Vanoli, G. (2013). Simplification state space representation for evaluating thermal bridges in building: Modelling, application and validation of a methodology. *Applied Thermal Engineering, 61*, 344-354.

Asdrubali, F., Baldinelli, G., Bianchi, F. (2012). A quantitative methodology to evaluate thermal bridges in buildings. *Applied Energy, 97,* 365-373.

ASHRAE. (2013). ASHRAE Handbook of Fundamentals (SI Edition): American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Barnes, B., Pagán-Vázquez, A., Liesen, R., Yu, J., & Alexander, N. (2013). *Window Related Thermal Bridges.* Paper presented at the Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference, Florida.

Berggren, B., Wall, M. (2013). Calculation of thermal bridges in (Nordic) building envelopes - Risk of performance failure due to inconsistent use of methodology. *Energy and Buildings, 65*, 331-339.

Capozzoli, A., Gorrino, A., Corrado, V. (2013). A building thermal bridges sensitivity analysis. *Applied Energy, 4*, 229-243.

Cappelletti, F., Gasparella, A., Romagnoni, P., & Baggio, P. (2011). Analysis of the influence of installation thermal bridges on windows. *Energy & Buildings, 43*, 1435-1442.

Ge, H., & Baba, F. (2015). Dynamic effect of themal bridging on the energy performance of a low-rise residential building. *Energy & Buildings, 105*, 106-118.

Hanam, B., Jaugelis, A., Finch, G. (2014). *Energy performance of windows: Navigating North American and European standards*. Paper presented at the 14th Canadian Conference on Building Science and Technology, Toronto.

Ibrahim, M., Biwole, P.H., Wurtx, E., Achard, P. (2014). Limiting windows offset thermal bridge losses using a new insulating coating. *Applied Energy, 123*, 220-231.

Kesik, T., Saleff, I. (2005). *Differential durability, building life cycle and sustainability*. Paper presented at the 10th Canadian Conference on Building Science and Technology.

Konstantinou, T., & Knaack, U. (2011). Refurbishment of residential buildings: a design approach to energy-efficiency upgrades. *Procedia Engineering, 21*, 666-675.

Kosny, J., Misiopecki, C., Fallahi, A., Shukla, N., duPont, W., Carbary, L. (2014). Thermal Design of window-wall interface in wall energy retrofits using high-performance vacuum insulation. *ASHRAE Transactions, 120*(2), 90-106.

LBNL, Lawrence Berkeley National Laboratory (2015). THERM 7.4 & WINDOWS 7.4 software retrieved from: https://windows.lbl.gov/software/therm/therm.html, accessed Sept. 2015.

LBNL, Lawrence Berkeley National Laboratory (1998). THERM 2.0 Program Description.

Retrieved from: https://windows.lbl.gov/software/therm/6/THERM63_docs.htm. Accessed Sept, 2015

LBNL Lawrence Berkeley National Laboratory (2013). THERM 6.3/WINODW 6.3 NFRC Simulation Manual/ retrieved from: https://windows.lbl.gov/software/therm/6/THERM63_docs.htm . accessed Sept. 2015.

Maref, W., Van Den Bossche, N., Armstrong, M., Lacasse, M.A., Glazer, R. (2011). Condensation risk assessment on box window: the effect of the window-wall interface. *Journal of Building Physics, 36*(1), 35-56.

Misiopecki, C., Jelle, B. P., Decheva, L. M., & Gustavsen, A. (2013). *Practical Methods for Ensuring Energy-Efficient Window-to-Wall Connections.* Paper presented at the Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference, Florida.

Morrison Hershfield (2014). *Building Envelope Thermal Analysis (BETA) Guide*. Retrieved from British Columbia: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/power-smart/builders-developers/final-mh-bc-part-1-envelope-guide.pdf Accessed Sept., 2015

Morrison Hershfield (2015). *Accounting for Thermal Bridging at Interface Details: A Methodology for De-Rating Prescriptive Opaque Envelope Requirements in Energy Codes*. Retrieved from British Columbia: https://www.bchydro.com Accessed Sept., 2015

O'Brien, M. (2005). Finding a better measure of fenestration performance: An analysis of AAMA condensation resistance factor. *Interface*, 4-10.

Pelss, M., Blumberga, A., & Kamenders, A. (2010). Thermal bridge impact on the heating demand in a low-energy house. *Scientific Journal of Riga Technical University, 4*, 76-80.

Sierra, F., & Maksoud, T. (2015). Impact of simplification of the methodology used to assess the thermal bridge of the head of an opening. *Energy & Buildings, 87*, 342-347.

Totten, P. O. (2008). The effects of thermal bridging at interface conditions. Retrieved from http://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BEST/BEST1_034.pdf Accessed July, 2015

Touchie, M. F., Pressnail, K.D., Tzekova, E.S. (2012). *Energy savings by retrofitting multi-unit residential buildings: Case studies*. Paper presented at the BEST 3, Atlanta. https://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BEST/best3_touchie.1.7.pdf Accessed July, 2015

Touchie, M. F., Pressnail, K.D., Tzekova, E.S. (2014). *Assessing potential energy retrofits of multi-unit residential buildings in the Greater Toronto area.* Paper presented at the 14th Canadian Conference on Building Science and Technology, Toronto.

Ueno, K. (2011). *Residential exterior wall super-insulation retrofit detail and analysis*. Paper presented at the Thermal Performance on the Exterior Envelopes of Whole Buildings XI International Conference, Florida.

Wang, Q., Augenbroe, G., Sun, Y. (2014). *The role of construction detailing and workmanship in achieving energy efficient buildings.* Paper presented at the Construction Research Congress, Atlanta.

White, D. (2009). *Thermal bridge analysis for the PHPP.* Paper presented at the Passive House Conference 2009, Frankfurt.