XVI International Conference on Durability of Building Materials and Components
DBMC 2023, China
K.F. Li and D.P. Fang (Eds)

Analysis of Thermal Bridges in Concrete and Cross-Laminated Timber (CLT) Constructions: A Numerical Study

Zegeye A. and Tariku F.

Building Science Center of Excellence, British Columbia Institute of Technology,
Vancouver, Canada, azegeye1@my.bcit.ca (Zegeye A.), Fitsum_Tariku@bcit.ca (Tariku F.)

Abstract. *The thermal efficiency of a building envelope relies on various factors, including insulation resistance, continuity, the thermal conductivity of structural materials, and the presence of thermal bridges. This study focuses on studying the thermal performance of thermal bridge details in two construction types: concrete and Concrete and Cross-Laminated Timber (CLT). For the study, two common building envelope details with significant thermal bridges are considered, balcony and intermediate wall-to-floor connections. Utilizing the finite element program COMSOL Multiphysics, hourly transient simulations were conducted over a one-year period to assess the heat loss/gain associated with thermal bridges, considering daily, seasonal, and annual heat flow for two diverse climatic conditions (hot weather Houston-Climate Zone 2 and cold weather Toronto-Climate Zone 6). The findings demonstrate that thermal bridges constructed from CLT outperformed those made of concrete. In Toronto, the annual heat flow for the concrete balcony was 146% higher compared to CLT, while in Houston, it was 67% higher. However, this trend was significantly reduced for the wall-to-floor detail, with a concrete detail showing a 13% increase in heat flow for Toronto and a 7% decrease in annual heat flow for Houston. Furthermore, the dynamic analysis revealed notable heat flow magnitude changes in the balcony detail, highlighting the importance of thermal conductivity, while the wall-to-floor detail exhibited dampening fluctuations in heat flow, emphasizing the material's heat capacity importance in this context.*

Keywords: *Thermal Bridge; CLT; Energy Performance; Transient Heat transfer; Thermal Mass*

1 Introduction

In 2021, buildings accounted for 30% of the world's total energy consumption and contributed to 27% of the overall energy-related emissions (IEA, 2022). Government policies on building design have been becoming stringent in order to meet the net zero carbon and energy targets. Achieving the net-zero goal requires a substantial reduction in building energy consumption, which is directly linked to the performance of the building envelope.

Improving the thermal efficiency of the building envelope is the most effective approach to reducing greenhouse gas emissions, as it plays a vital role in managing heat loss and minimizing energy consumption. While increasing insulation within the building envelope is widely recognized as a primary method for enhancing thermal efficiency, it is crucial to address thermal bridges adequately to minimize energy loss and the detrimental effects of condensation (Tariku et al. 2015). Therefore, incorporating adequate thermal insulation at the intersection of walls and balcony slabs becomes essential to reduce condensation potential (Hemmati et al. 2017). In addition to ensuring the continuity of thermal insulation and incorporating thermal breaks, the utilization of materials with low thermal conductivity for building construction can be considered as a potential strategy for mitigating thermal bridges.

This paper aims to examine thermal bridges in concrete and Cross Laminated Timber (CLT) constructions, structures with relatively high and low thermal conductivities, respectively. The two common thermal bridge building envelope details: intermediate walls-to-floor and balcony constructed from concrete and CLT were considered for the study. The thermal performance of these exterior insulated thermal bridge details under cold and hot climate conditions, Toronto (Climate Zone 6) and Houston (Climate Zone 2), respectively, were investigated. A finite element software called COMSOL Multiphysics was utilized to conduct an hourly transient simulation over a one-year period, and the heat gain and heat loss through the building envelope details during the winter and summer seasons were compared.

2 Building Envelope Detail Description

The two structural building materials examined in this study are concrete and Cross Laminated Timber. For the CLT structures, Spruce-Pine-Fir (SPF) type with a thermal conductivity of 0.12 $W/m \cdot K$ (FPInnovation, 2019) was utilized, employing a 3-ply configuration for the walls and a 5-ply configuration for the floors. The concrete building is assumed to be built with 8 inches thick concrete, thermal conductivity of 1.8 $W/m \cdot K$. The buildings are cladded with XPS-based exterior insulation finishing systems (EIFS). The schematic diagrams of the CLT and the concrete wall-floor and balcony details are presented in Figure 1. The buildings are presumed to comply with the ASHRAE 90.1 (2022) thermal resistance requirement for mass buildings in the respective climate zone. The variation in thermal conductivity between concrete and CLT, however, necessitates different exterior insulation thicknesses to attain the same overall thermal resistance value. For instance, in Climate Zone 6, in order to meet the ASHRAE 2022 requirements, the concrete building necessitates 2.5 inches of XPS insulation, whereas CLT only requires 2 inches. Similarly, in Climate Zone 2, concrete requires 1.5 inches of XPS insulation, while CLT requires approximately 0.75 inches.

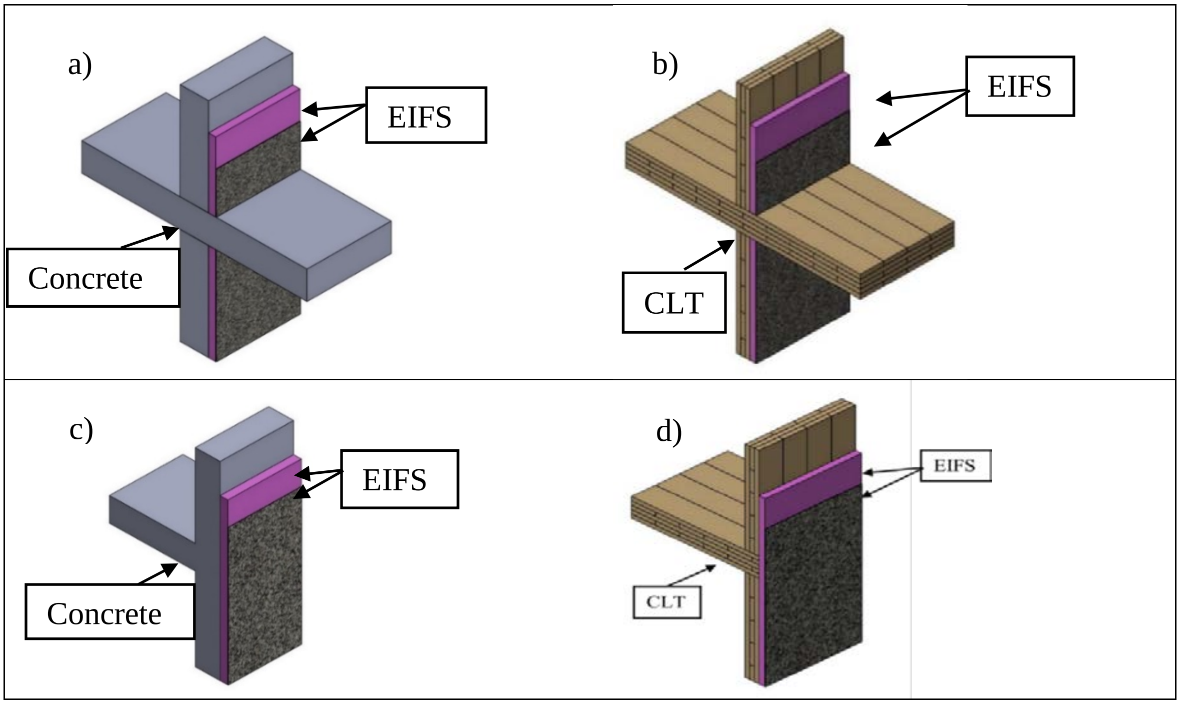

Figure 1. Schematic diagram of balcony and Intermediate wall-to-floor details a) Concrete - balcony, b) CLT – balcony, c) Concrete – Wall-to-floor, d) CLT – Wall-to-floor

3 Numerical modeling setup

The numerical calculation is performed using the finite element software COMSOL Multiphysics 6.1 which solves the energy balance equation, Equation (1) at every single mesh node for each time step.

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=\frac{\partial T}{\alpha.\partial t} \tag{1}$$

Where T is the Temperature, t is the time, α is the thermal diffusivity of material, and X and Y are the cartesian coordinates axis.

The computational domain of each detail is defined by the adiabatic cut-off plane (Figure 2), which is determined based on the point at which either the inner or outer surface temperature deviates by more than ΔT=0.2K (Martin et al., 2012). To enhance computational efficiency, a symmetry plane was employed to reduce the full geometry. A mesh sensitivity analysis was conducted to ensure that the solution results are not affected by the mesh. Five different mesh types (Normal, Fine, Finer, Extra fine, and Extremely fine) were assessed. The "Finer" mesh type provided a solution with a heat flux percentage difference of only 0.019% compared to the coarser "Fine" mesh type, and further mesh refinements did not result in heat flux change. Accordingly, the ‘Finer’ mesh was deemed to be appropriate to use for the study.

Prior to use, the capability of COMSOL for the problem at hand was assessed by comparing its simulation results with the ISO 10211 reference solutions provided for test case 3. The temperature and heat flux values obtained from the COMSOL simulation were in good agreement with the reference solutions, with deviations of only 0.04°C and 0.1%, respectively. The deviations fall within the allowable range, confirming the suitability of COMSOL for the study.

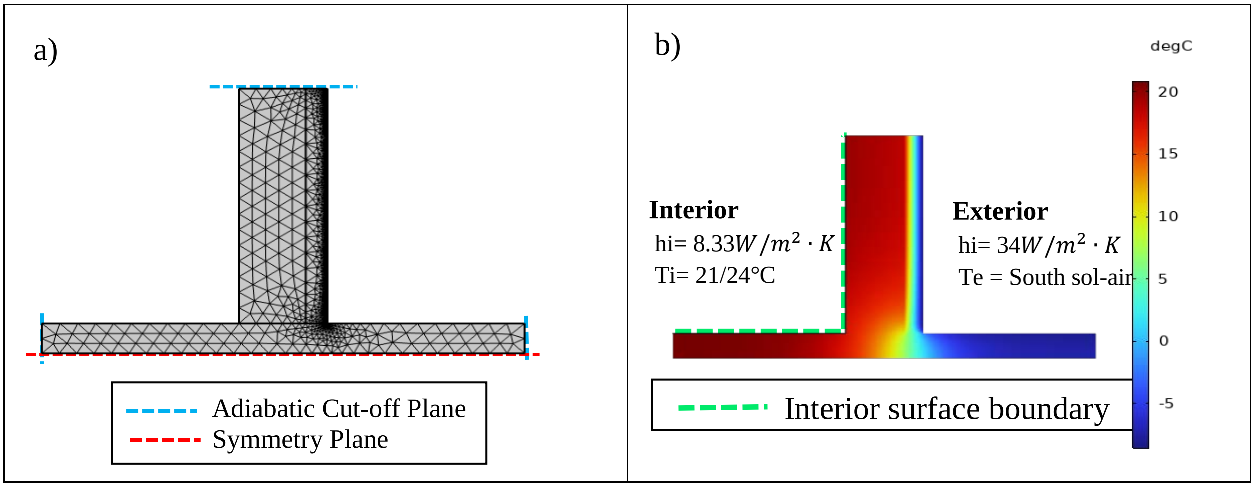

Figure 2. a) Typical mesh and computational domain showing cut-off plane and symmetry plane b) Heat flux contour plot and showing the surface boundary and boundary conditions

The heat transfer through the building envelope details were modeled using one-year weather data, with the exterior temperature derived from the South sol-air temperature for Toronto and Houston. The interior temperature was kept constant at 21°C, except during the summer months (June-August) in Toronto, where it was set to 24°C. In contrast, for Houston, a constant interior temperature of 24°C was maintained, except during the winter months (November-February), where it was lowered to 21°C. The heat transfer coefficients of 34 $W/m^2 \cdot K$ and 8.33 $W/m^2 \cdot K$ were assigned from (ASHRAE, Handbook of Fundamentals, 2017) to the exterior and interior surface boundaries, respectively.

4 Simulation Result

In this section, first, the impact of thermal bridges on the concrete and CLT buildings is presented, followed by a detailed heat flow analysis of the four distinct cases: balcony and Wall-to-floor details under Toronto and Houston weather conditions. The analysis encompassed daily, monthly, and annual heat flow through the building envelope details. **Relative impacts of thermal bridge details in Concrete and CLT envelope systems**

Table 1 presents the heat flow comparison between exterior walls with and without thermal bridges, *Wall_TB* and *Wall_Clear* in the table, respectively, for Toronto and Houston climate conditions. The inclusion of the balcony detail in the concrete building results in an increase of the annual heat flow across the interior boundary surfaces (summation of heat loss and heat gain) by 62% for Toronto and 46% for Houston. The thermal bridge effect of intermediate wall-to-floor detail is not as prominent as the balcony detail. It resulted in an increase of heat flow by 7% for concrete and 3% for CLT in both climate zones. The significantly lower heat transmission observed in the wall-floor detail is attributed to the continuous exterior insulation covering the slab, which improves energy efficiency. In contrast, the presence of a balcony slab creates a discontinuity in the exterior insulation, leading to considerable heat loss and higher energy consumption associated with the concrete balcony detail.

Table 1.Heat flow comparison of clear wall and thermal bridge for Toronto and Houston climate conditions

Location	Detail	Material	Wall_TB(Wh) [Annual]	Wall_Clear(Wh) [Annual]	Difference(%)
Balcony	**Toronto**	**Concrete**	221061	116754	61.8
		CLT	120324	112445	6.8
	Houston	**Concrete**	131041	82440	45.5
		CLT	101298	98016	3.3
Wall-to-Floor	**Toronto**	**Concrete**	124099	116149	6.6
		CLT	116907	112266	4.1
	Houston	**Concrete**	88001	82440	6.5
		CLT	101157	98016	3.2

4.2 Dynamic responses of concrete and CLT thermal bridge details

The dynamic heat flows through the concrete and CLT thermal bridge details were examined by analyzing three days of simulation results during the winter season (February 15-17) and the summer season (July 15-17). In the Toronto climate condition during winter, the heat loss in the concrete balcony detail was nearly twice high as that of the CLT balcony detail (Figure 3a). The peak heat gains in both CLT and Concrete details are equivalent in Houston, while the heat loss at night is slightly higher in the CLT building (Figure 3b). Similarly, in the summer season, the heat loss in both construction details is similar at night in Toronto while the peak heat gain through the concrete detail is ~50% higher than that of the CLT detail during daytime (Figure 4c). Similar to the winter-Toronto case, the CLT detail outperformed the concrete detail by a significant margin (approximately two times lower) in the summer-Houston case (Figure 4d). These results suggest that the performance difference between the two construction details widens for extreme weather conditions, cold winter, and hot summer periods. The daily heat flow analysis of the exterior insulated wall-to-floor detail showed a small difference between CLT and concrete. Plots for the extreme cases Winter-Toronto and summer-Houston are shown in Figure 5a and Figure 5b, respectively. Others are not shown here due to space limitations. In the Toronto climate during winter (Figure 5a), the lower thermal conductivity of CLT resulted in lower heat flow compared to concrete. However, in the opposite summer-Houston case (Figure 5b), the high thermal storage property of concrete reduced the peak heat gains but at the same time exhibited higher gains during the nighttime as it dissipated stored heat.

Examination of the dynamic heat flow and temperature responses of the two details in two climates and seasons led to the following observations. First, the shift in the magnitude and the dampening in heat flow fluctuation observed in the balcony and wall-floor details, respectively, point to the significance of thermal conductivity and heat capacity in the respective details. Furthermore, it was confirmed that the temperature differences at the interior corner of the balcony and wall-floor details were negligible except for the winter-Toronto case where a 3°C temperature difference was observed in the former detail.

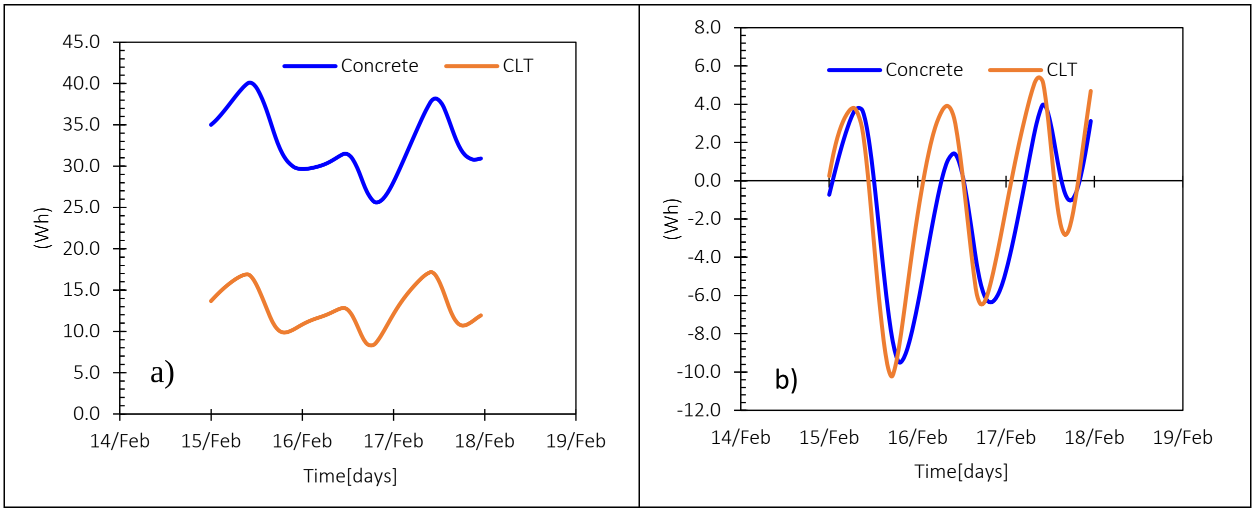

Figure 3. Three-day dynamic response of balcony detail a) Toronto winter, b) Houston winter

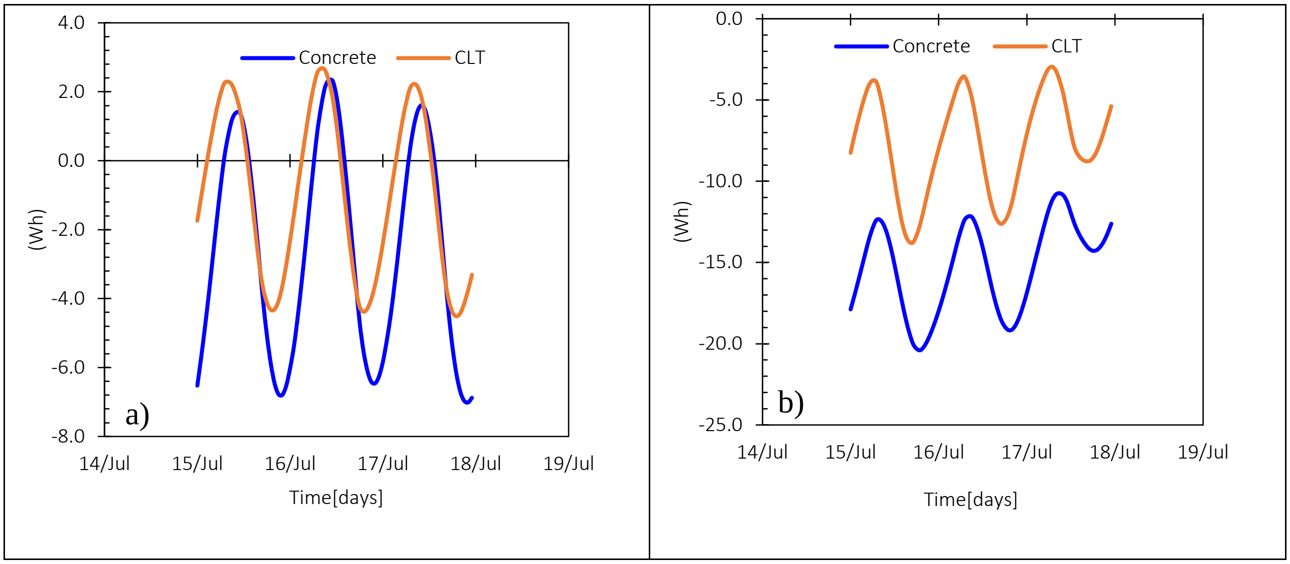

Figure 4.Three-day dynamic response of balcony detail a) Toronto summer, b) Houston summer

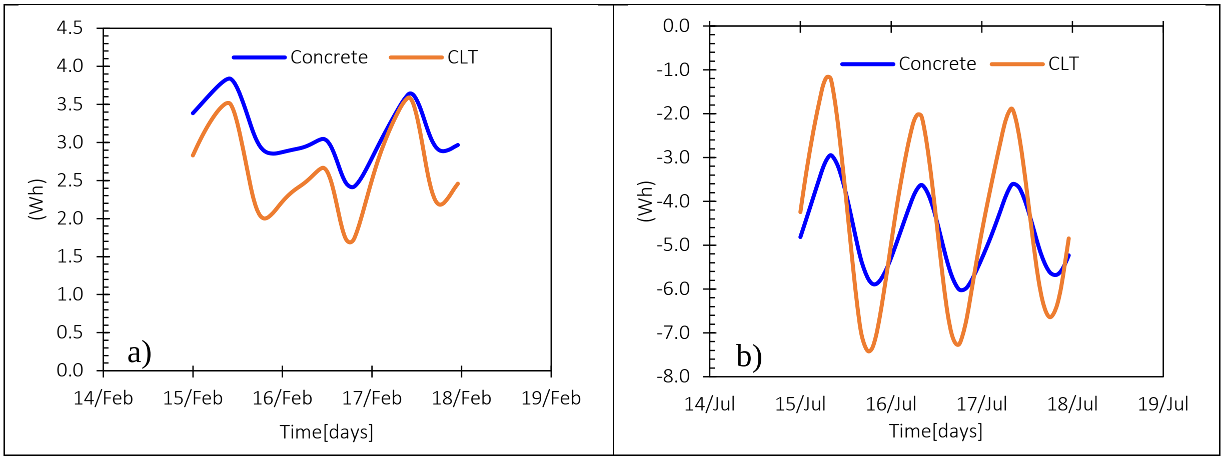

Figure 5. Three-day dynamic response of wall-to-floor detail a) Toronto winter, and b) Houston summer

4.3 Comparison of the seasonal and annual heat flows through concrete and CLT details

Monthly heat flow through the details was further examined, with separate calculations for heating and cooling energy. For Toronto climate, the maximum monthly heating energy for CLT-balcony reaches approximately 10.6 kWh, whereas concrete-balcony requires as high as 27 kWh (154.7% more). In terms of cooling energy, the maximum heat gain occurs in July, with 2.7 kWh for concrete-balcony and 1.2 kWh for CLT-balcony (Figure 6a), which is 55.5% lower. In Houston, the maximum heat loss was observed in December, approximately 10 kWh for concrete and 5 kWh for CLT (50% difference). Similarly, the highest heat gain occurred in July, with around 11 kWh for concrete and 6 kWh for CLT (about a 45% difference) (Figure 6b).

Comparing the wall-to-floor detail in Toronto during winter (Figure 6c), CLT performs better with a heating load of 5.4 kWh in December, while concrete requires around 16.6% more. However, during the summer, the differences in heat gains between the two construction materials are negligible, although concrete has slightly lower heat gain. In Houston's climate, the maximum monthly heat loss was approximately 2.6 kWh for both concrete and CLT, observed in December. Similarly, July represented the month with the highest heat gain, requiring over 3 kWh of cooling energy for both details (Figure 6d).

The total heat flow for the entire year, considering both heat losses and gains that cross the interior surfaces of the details, is presented in Table 2. When considering balcony detail in the Toronto climate, the heat flow in concrete is significant, a 145% increase when compared to CLT. In Houston climate condition, the heat flows are 90 kWh for concrete and 55 kWh for CLT. This indicates that concrete consumes approximately 67% more energy than CLT.

Regarding the wall-to-floor detail, the overall annual heat flow in concrete amounted to approximately 39 kWh in Toronto, which is 12.6% higher than that of CLT. However, if the insulation location were changed to the interior side of the wall, this percentage difference would increase significantly to 107.6%. In the case of wall-to-floor detail in Houston, concrete exhibited a 12% reduction in annual heat flow compared to CLT. However, if the exterior insulation were repositioned to the interior, this percentage difference would increase significantly to 56.6%. In contrast to that of wall-floor detail, insulation position in balcony detail has no significant effect since the thermal bridge element cuts the insulation in both the interior and the exterior insulation cases.

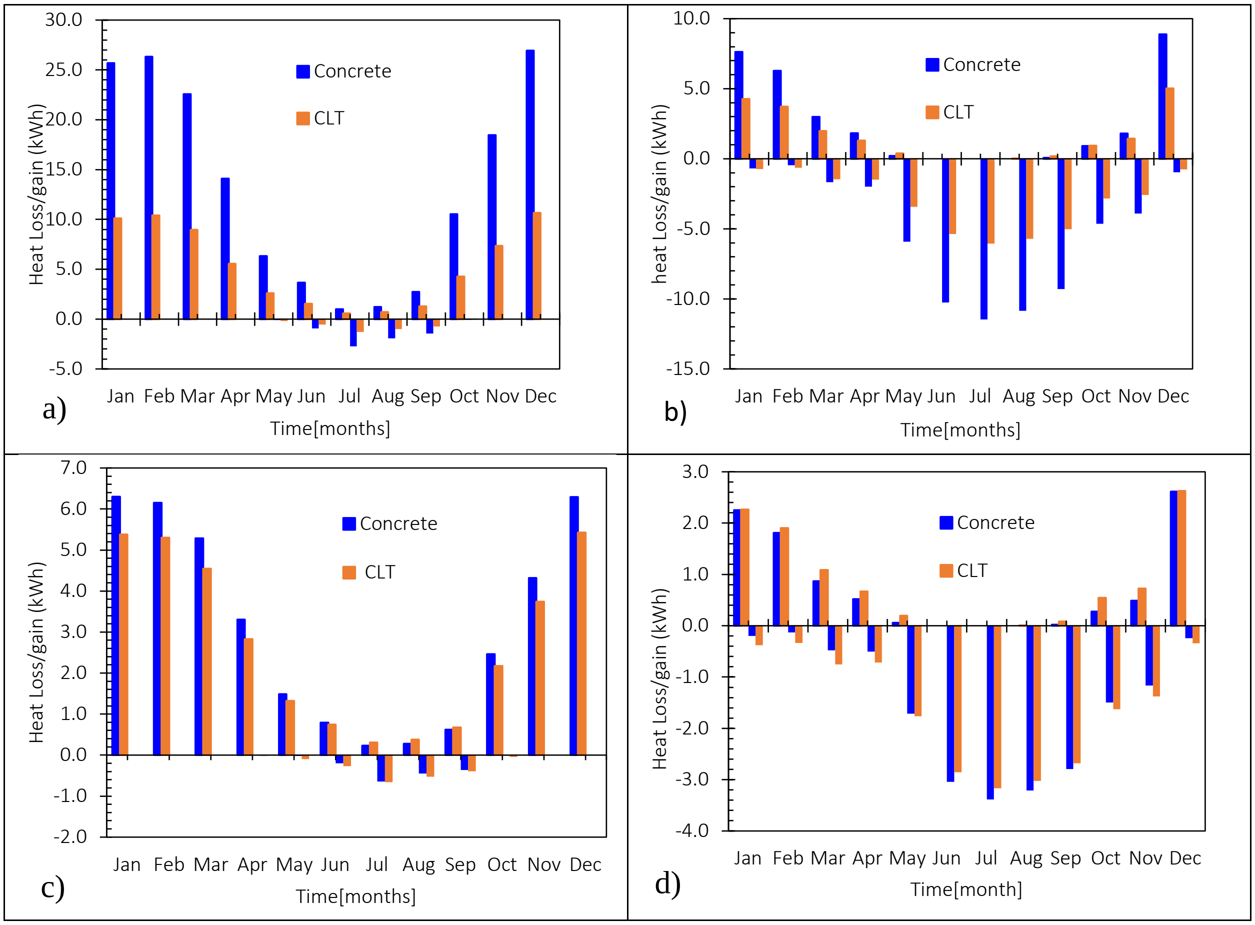

Figure 6. Monthly heat loss/gain over a year a) Balcony-Toronto, b) Balcony-Houston, c) Wall-to-Floor-Toronto, d) Wall-to-Floor-Houston

Table 2. Annual heat flow of the two envelope details

Detail	**Location**	**Heat Flow (kWh)**		**Difference (%)**
		Concrete	**CLT**	
Balcony	Toronto	166.7	67.9	145.5
	Houston	92.6	55.3	67.4
Wall-to-Floor	Toronto	39.2	34.8	12.6
	Houston	27.3	29.1	6.8

5 Conclusion

In this study, an extensive investigation was conducted to assess the impact of thermal bridge details in concrete and CLT constructions under different climate conditions of cold Toronto and hot Houston weather conditions. In both climate zones, heat flow through the concrete balcony detail is significantly higher (61.8% for Toronto and 45.5% for Houston) when compared to that of constructed CLT, which only increased by 6.8% and 3.3% for Toronto and Houston, respectively. Construction type has minimal effect on wall-floor detail thermal bridge if insulated on the exterior. The increases in heat flow through wall-floor detail in Toronto are 4.1% and 6.6%, for CLT and concrete, respectively. Remarkably, the location of insulation in balcony detail emerges as a significant factor, as it drastically changes the performance of the wall-to-floor detail examination of the hour heat flux profiles suggests that while thermal conductivity governs the heat flow in balcony detail, the heat capacity of the materials shapes the heat flux profiles in wall-floor detail. In general, CLT construction has superior performance for all geometries except for the wall-to-floor detail in the Houston climate, where concrete exhibits slightly better performance. Furthermore, the balcony detail exhibits a notable temperature variation of approximately 3°C between the two construction types. These findings emphasize the importance of careful material selection and insulation placement in achieving energy-efficient building designs that cater to specific climate conditions and operational requirements.

References

ASHRAE. (2017). *Handbook of Fundamentals.* Atlanta.

ASHRAE. (2022). *Standard 90.1: Energy Standard for Buildings Except for Low-Rise Residential Buildings.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

COMSOL AB. (n.d.). *COMSOL Multiphysics*. Retrieved from https://www.comsol.com

FPInnovation. (2019). *Canadian CLT Handbook.*

Hemmati, F., Vaseghi, A., & Tariku, F. (2017). Risk of Condensation Analysis of Common Concrete Balcony Configurations. *ASHRAE Winter Conference.* Las Vegas.

IEA. (2022). *Buildings.* Retrieved from IEA: https://www.iea.org/reports/buildings

ISO 10211: 2007 Thermal bridges in building construction–Heat flows and surface temperatures–detailed calculations.

Martin, K., Escudero, C., Erkoreka, A., Flores, I., & Sala, J. M. (2012). Equivalent wall method for dynamic characterization of thermal bridges. *Energy and Buildings*, 704-714.

Tariku, F., Kumaran, K., & Fazio, P. (2015). Application of a Whole-Building Hygrothermal model in energy, durability, and indoor humidity retrofit design. *Journal of Building Physics*, 3-34.