Assembly-Scale and Whole-Building Energy Performance Analysis of Ultra-High-Performance Fiber-Reinforced Concrete (UHP-FRC) Façade Systems

Bahram Abediniangerabi,* (corresponding author) – Graduate Research Assistant, Department of Civil Engineering, The University of Texas at Arlington, 416 S. Yates St., Arlington, TX 76010 USA, Email: bahram.abediniangerabi@uta.edu
Seyed Mohsen Shahandashti – Professor, Department of Civil Engineering, The University of Texas at Arlington, 416 S. Yates St., Arlington, TX 76010 USA, Email: mohsen@uta.edu
Bradley Bell – Professor, School of Architecture, The University of Texas at Arlington, 601 W. Nedderman Dr., Arlington, TX 76019 USA, Email: bbell@uta.edu
Shih-Ho Chao – Professor, Department of Civil Engineering, University of Texas at Arlington, 416 S. Yates St., Arlington, TX 76010, Email: shchao@uta.edu
Atefe Makhmalbaf – Professor, School of Architecture, The University of Texas at Arlington, 601 W. Nedderman Dr., Arlington, TX 76019 USA, Email: atefe.makhmalbaf@uta.edu

Abstract:

Majority of building energy consumption is used to heat and cool enclosed spaces. An innovative ultra-high-performance fiber-reinforced concrete (UHP-FRC) façade system has the potential to reduce building energy consumption. The objectives of this research are (1) to analyze the heat and moisture transfer within the UHP-FRC façade panels, and (2) assess the energy performance of a proposed UHP-FRC façade system in comparison with conventional sandwich panel façade system in commercial building context (large office, medium office, and small office buildings). A transient hygrothermal analysis is conducted to investigate heat and moisture transfer within the UHP-FRC façade system and evaluate the risk of mold growth in internal layers of the façade system for different boundary conditions. A simulation-based building energy performance analysis is conducted to investigate the energy performance of the UHP-FRC panel system in the commercial building context (three DOE prototype commercial buildings are used as building context) in fifteen locations with different climate and weather conditions (45 scenarios). The results of the hygrothermal analysis showed that the UHP-FRC panel assembly's performance is superior to the conventional panel regarding combined heat and moisture transfer. Although the result of building energy simulations showed that the energy savings of using the UHP-FRC panel depend on the building type and climate condition, in 44 out of 45 scenarios, the total energy savings were positive. It is expected that the results of this research help develop the next generation of high-performance energy-efficient façade systems using UHP-FRC.

Keywords:

Ultra-High-Performance Fiber-Reinforced Concrete (UHP-FRC); Building façade systems; assembly-scale; whole-building energy performance analysis; thermal bridging; and hygrothermal Analysis

1. Introduction

Residential and commercial buildings use approximately 40% of energy use in the United States on an annual basis (U.S. EIA, 2015). The large proportion of this amount of energy is consumed for heating and cooling enclosed spaces in buildings (Park et al., 2015). Building façade systems that control heat transmission between outdoor and indoor environments play a critical role in the amount of energy savings of buildings (Karasu, 2015).

In recent years, researchers have developed energy-efficient façade systems exploiting innovative solutions, such as Fiber-reinforced Plastic (FRP) (Abdou et al., 1996), phase change materials (Sadineni et al., 2011; Iommi 2018), thermal resistance materials (Sadineni et al., 2011), and dynamic insulation materials (Park et al., 2015). These studies provided valuable insights into the energy performance of innovative façade systems. However, no study investigates innovative façade systems in both assembly scale and building context.

Recent advances in concrete material innovation, such as Ultra-High-Performance Fiber Reinforced Concrete (UHP-FRC), offer the opportunity to develop more energy-efficient building envelope systems to reduce the heat loss in buildings (Shahandashti et al., 2017; Abediniangerabi et al., 2018). UHP-FRC as a new class of concrete provides very high compressive strength (18 to 30 ksi [124 to 207 MPa]) and tensile ductility. The compressive strength of UHP-FRC is about six times higher than conventional concrete with a post-cracking tensile strain up to 0.6% without strength degradation (Aghdasi et al., 2016). Table 1 illustrates the differences between a typical conventional concrete and UHP-FRC (Kaka and Chao, 2018).

Table 1. Comparison of typical conventional concrete and UHP-FRC (Kaka and Chao, 2018)

Properties	Conventional Concrete	UHP-FRC
Ultimate Compressive Strength	< 8,000 psi (55 MPa)	18,000 to 30,000 psi (124 to 207 MPa)
Early (24-hour) compressive strength	< 3000 psi (21 MPa)	10,000 – 12,000 psi (69 to 83 MPa)
Flexural Strength	< 670 psi (4.6 MPa)	2,500 to 6,000 psi (17 to 41 MPa)
Shear strength	< 180 psi (1.2 MPa)	> 600 psi (4.1 MPa)
Direct Tension	< 450 psi (3 MPa)	up to 1,450 psi (10 MPa)
Rapid Chloride Penetration Test*	2000-4000 Coulombs passed	Negligible (< 100 Coulombs passed)
Ductility	Negligible	High ductility
Ultimate Compressive Strain, ε_{cu}	0.003	0.015 to 0.03
Confining	Negligible	High confining capability

* Ahlborn et al. 2011

It is possible to consider altering building strategies by creating very thin and lightweight panels by replacing conventional concrete reinforced by mild steel reinforcing bars with UHP-FRC (Bell et al., 2016). A UHP-FRC façade panel could have a thicker insulation layer (5 inches or 12.7 cm) compared with the conventional panel (2-inch or 5.1 cm insulation layer) (Bell et al., 2016). Although it is expected that buildings enhanced with UHP-FRC panels result in lower building energy consumption than buildings with the conventional panels due to the thicker insulation layer, the energy performance assessment of innovative façade systems, such as UHP-FRC panels, could be misleading if the assessment is taken place either in assembly scale or building context. The objectives of this paper are analyzing the heat and moisture transfer within the UHP-FRC façade panels (in assembly scale) and assessing the energy performance of a proposed UHP-FRC façade system in comparison with conventional sandwich panel façade system in commercial building context (large office, medium office, and small office buildings).

2. Research Methodology

Figure 1 illustrates two different simulation-based methodology used to address two objectives of this paper. The evaluation of UHP-FRC façade systems is carried on in both assembly scale and building context. Thermal bridging analysis is conducted for the UHP-FRC façade panel systems and compared with the performance of conventional panel systems. Three different boundary conditions were considered for heat transfer analysis. A hygrothermal assessment is also conducted for both panels in transient-state to compare the moisture behavior within the panels in fifteen locations across the U.S. Three U.S. Department of Energy (DOE) commercial prototype buildings (large office, medium office, and small office buildings) are selected to evaluate the energy performance of UHP-FRC panels in the context of commercial buildings and compare it with the energy performance of conventional panels. The façade systems of these three building models are replaced by two competing façade alternatives (conventional panels and UHP-FRC panels), and the building models are simulated in 15 different locations using *EnergyPlus*^{TM}. Finally, the result of energy simulations is compared for buildings with competing façade systems, and the energy saving percentages are calculated in favor of buildings with the UHP-FRC façade systems.

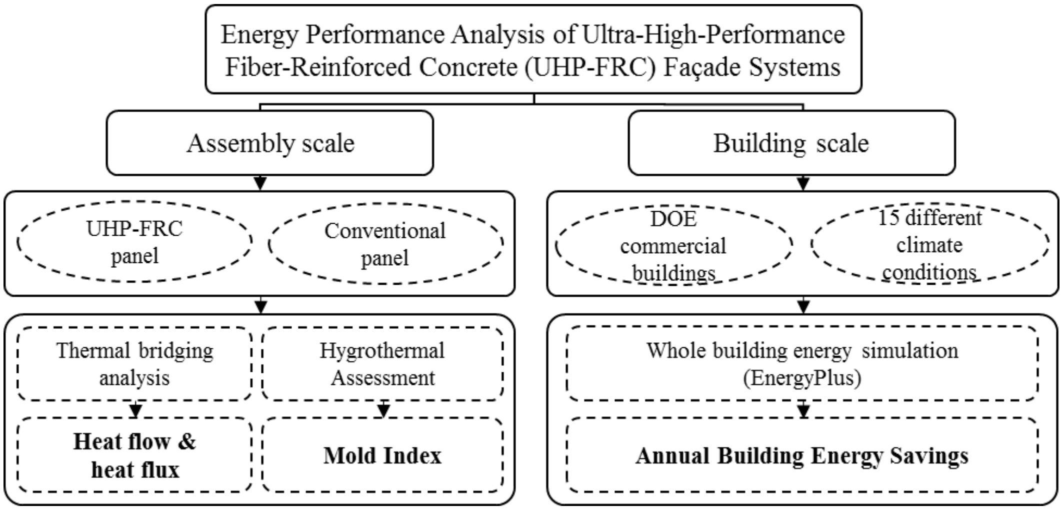


Figure 1. Simulation-based methodology for the energy performance analysis of UHP-FRC façade systems

2.1. Conventional and UHP-FRC Façade Systems

The standard conventional panel is a 3 ft. by 3 ft. (91.4 cm by 91.4 cm) panel with a weight of 676 lbs (307 kg). This panel is commonly used in the U.S. construction industry (Losch et al., 2011). It consists of three layers (two structural and one isolation layers). The facing and backing layers are 3 inches (7.62 cm) structural wythes that are structurally reinforced with a wire mesh (6 inches (915.24 cm) by 6 inches (15.24 cm)). The wire mesh is attached to a NO.4 (1/2 inch (1.27 cm)) rebar around the panel parameter. Standard connection ties (thermos-mass t series fiberglass) are used to connect the wythes through a 2 inch (5.08 cm) thick expanded polystyrene (EPS) rigid insulation layer (Bell et al., 2016). A standard 7-sack Portland cement mix is used to produce compression strength of 5,000 psi (34.5 MPa) for the facing mix and 7,000 psi (48.3 MPa) compression strength for the backing mix.

The innovative UHP-FRC pre-cast sandwich panel is comparable to the industry standard panel. Same as conventional panels, this panel consists of two structural layers and one insulation layer. Two 1-1/2 inches (3.81 cm) UHP-FRC layers are used for facing and backing wythes, and a 5 inch (12.7 cm) extruded polystyrene (XPS) rigid insulation is placed between two structural wythes. The UHP-FRC panel is 8 inch (20.32 cm) thick with the weight of 338 lbs. The structural layers are connected with standard connection ties (thermos-mass CC130 fiberglass connector). Removing reinforcing bars in the UHP-FRC helps to provide more space for the insulation layer. Figure 2 illustrates the configurations of both conventional and UHP-FRC façade panels.

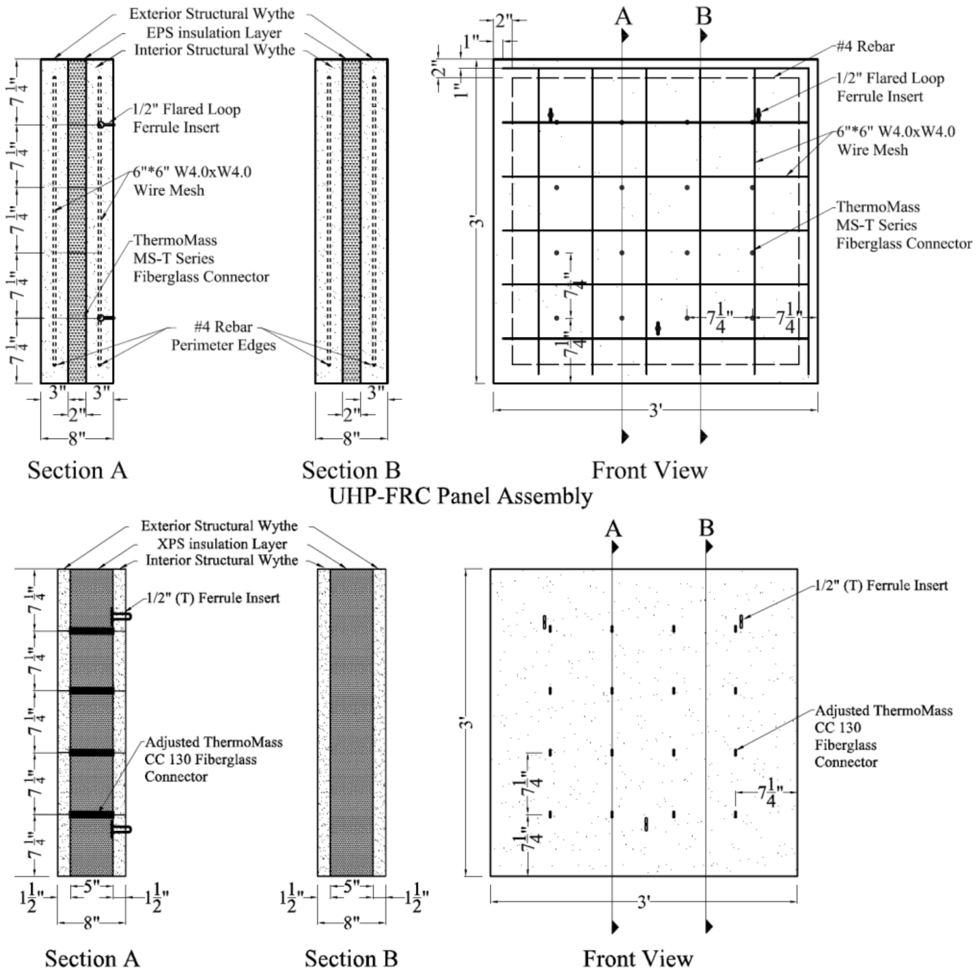


Figure 2. Conventional and UHP-FRC façade panels configuration (Abediniangerabi et al., 2018)

2.2. Thermal Bridging and Hygrothermal Assessment of UHP-FRC and Conventional Panels

Numerical simulations are carried out to investigate the heat and moisture transfer through the UHP-FRC and conventional panel assemblies and evaluate the risk of mold growth within the panels. These simulations are used to find the thermal and moisture linkages between the exterior and interior sides of the panels. Table 2 illustrates the thermal and hygrothermal properties of panel layers in both UHP-FRC and conventional panel assemblies used in the numerical simulations.

Table 2. Thermo-physical properties of UHP-FRC and conventional panel assemblies

Layer	Parameters	Conventional Panel	UHP-RFC Panel
Concrete	Thickness - D	7.62 cm (3 in)	3.81 cm (1.5 in)
	Density - ρ	2322 kg/m^3	2403 kg/m^3
	Porosity - P	0.7912 m^3/m^3	0.7912 m^3/m^3
	Specific heat capacity - C_p	832 J/kg-K	1010 J/kg-K
	Thermal conductivity - λ	2.31 W/m-K	1.77 W/m-K
	Vapor diffusion resistance - μ	18.58	18.58
	Initial moisture content - MC	19.22 kg/m^3	20 kg/m^3
Insulation	Insulation Type	EPS	XPS
	Thickness - D	5.08 cm (2 in)	12.7 cm (5 in)
	Density - ρ	28 kg/m^3	20 kg/m^3
	Porosity - P	0.99 m^3/m^3	0.99 m^3/m^3
	Specific heat capacity - C_p	645 J/kg-K	645 J/kg-K
	Thermal conductivity - λ	0.005769 W/m-K	0.005769 W/m-K
	Vapor diffusion resistance - μ	73.02	170.55
	Initial moisture content - MC	0.06 kg/m^3	0.13 kg/m^3

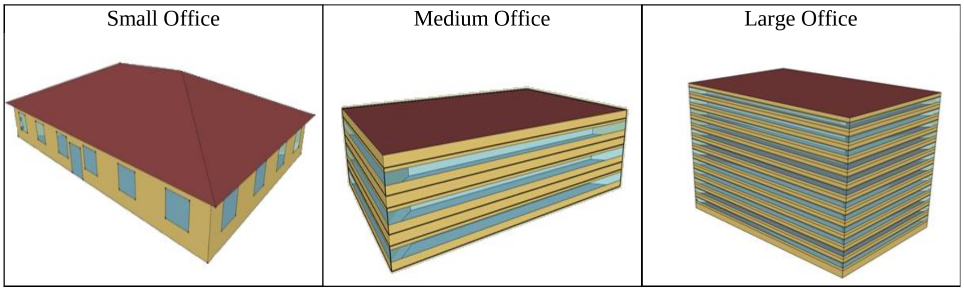
Building façade system is one of the major sources of heat loss in buildings. Heat losses occur through the elements of building façade panels as well as thermal bridges. Thermal resistance is usually lower in thermal bridges (Real et al., 2016). Hence thermal bridges initiate additional heat transfer between outdoor and indoor environments. Therefore, one of the necessities in the energy performance evaluation of new façade systems is the evaluation of thermal bridges. The thermal bridging analysis of both UHP-FRC and conventional panel assemblies is carried out to compare the energy performance of both panels. A finite element method is used to model the heat transfer behavior within the UHP-FRC and conventional panel assemblies. Finite Quadtree meshing algorithm is used for meshing, and THERM 7.4 (Mitchell et al., 2003) is used to model heat transfer.

One of the major challenges in using interior thermal insulation layer in building facade systems is the risk of moisture condensation and mold growth (Pavlík & Černý, 2009). Vapor condensation mostly occurs on the cold side of the insulation layer in exterior walls where water content increases (Finken et al., 2016). This condensation typically causes mold problems. Since a thicker insulation layer is used in the UHP-FRC panel assembly, the hygrothermal assessment of panel assemblies is conducted and compared. WUFI Pro 6.2 (Zirkelbach et al., 2007) is used to model a coupled moisture and heat transfer within the panel assemblies. WUFI Pro also provides the mold index (MI), which is a six-point scale index for assessing the risk of mold growth. Six and zero are the highest and lowest level for mold growth risk, respectively, and one is a tolerable level for this index. The hygrothermal analysis of both panels is carried out in fifteen locations within the U.S. for ten years. It is assumed that the panels are vertically installed in a direction that is most exposed to driving rain for each location. The indoor temperature and moisture loads are set according to ASHRAE 160 standard (heating setpoint: 21.1 °C, cooling setpoint: 23.9 °C, and relative humidity: 80% RH), and the initial moisture content and temperature for all the components are considered as constant (20 °C; 80% RH).

2.3. Building Energy Simulations of UHP-FRC and Conventional Panels in Commercial Building

2.3.1. DOE Commercial Prototype Buildings and Climate Zones

Three DOE commercial prototype buildings are used to represent the commercial building context in the energy performance analysis of the UHP-FRC panel. These prototype buildings, which are modeled based on ANSI/ASHRAE/IES Standard 90.1, are commonly used for whole building energy simulation analysis as a consistent baseline (U.S. Department of Energy, 2016a). Figure 3 illustrates the 3D model of DOE prototype buildings. The thermo-physical properties of façade panels in these three commercial building models are adjusted to reflect two competing façade systems in the building energy simulation models.



Small Office

Medium Office

Large Office

Figure 3. 3D model of DOE commercial buildings (U.S. Department of Energy, 2016a)

To represent the climate conditions in energy performance analysis of the UHP-FRC panels, DOE climate zones are used. These zones (weather data) provide consistent climate materials for all compliance methods and code sections for DOE and ASHRAE Standard 90.1-2004 (Briggs et al., 2003). The detailed characteristics of 15 typical locations (representative cities) used in this paper could be found in Abediniangerabi et al. (2018).

2.3.2. Whole Building Energy Simulations

Whole building energy simulations are used to estimate the energy uses of commercial building models. A variety of building energy simulation programs have been developed to estimate energy use of the buildings by simulating the complex interactions within buildings, such as BLAST, DOE-2.1E, ECOTECT, eQUEST, and EnergyPlus (Parent, 2002). EnergyPlus is widely used to estimate building energy performance in academia and building communities (Sailor, 2008). In this research, *EnergyPlus*$^{\text{TM}}$ is used to estimate the energy use of three commercial buildings in 15 different locations (45 scenarios). The simulation results are used to compare the performance of the UHP-FRC panel with the baseline conventional panel.

3. Results and Discussions

3.1. Results of Thermal Bridging and Heat Transfer Analysis

Figure 4 shows the results of thermal bridging analysis regarding heat transfer within the UHP-FRC and conventional panel assemblies in three different boundary conditions. Comparing thermal bridging results for both panels shows that the thermal bridging in the conventional panel is much higher than the thermal bridging in the UHP-FRC panel. Thermal bridging in conventional panels happens not only at the location of the connectors but also at the location of the structural rebars. It is clear that the combination of connectors and rebars is accelerating the thermal bridging in the conventional panel. In contrast, the heat transfer results for the UHP-FRC panel for all the boundary conditions show that the connectors are the only reason for thermal bridging. Moreover, the heat flux results for both panels show that as the temperature difference increases between indoor and outdoor environment, heat flux intensity increases in the conventional panel but not the UHP-FRC panel. Table 3 shows the results of thermal bridging analysis for both assemblies in detail. The heat flux in both panel assemblies shows that the UHP-FRC panel assembly performs better in all boundary conditions regarding thermal resistance. The R-value for UHP-FRC panel assembly was 0.87 m^2-K/W. On the other hand, the R-value for the conventional panel was 0.12 m^2-K/W.

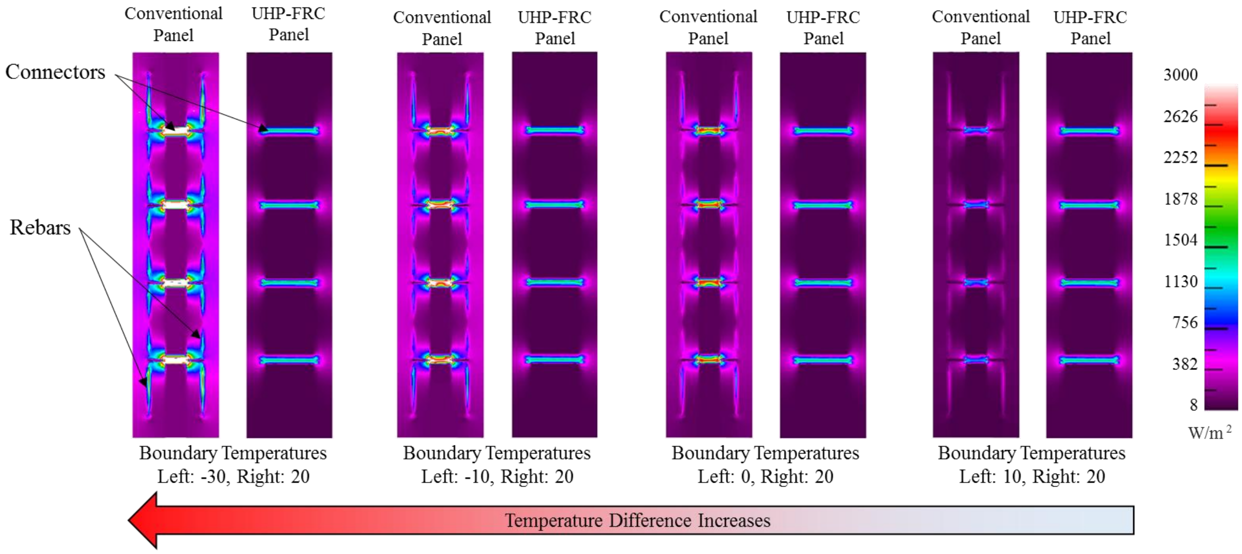


Figure 4. Heat flux magnitude in cross-section of UHP-FRC and conventional panel assemblies

Table 3. Heat flux in UHP-FRC and conventional panel assemblies for different boundary conditions

Boundary temperature (Out-In)	Conventional panel	UHP-RFC panel
-30 °C - 20 °C	472.2 W/m^2	203.1 W/m^2
-10 °C - 20 °C	300.5 W/m^2	129.2 W/m^2
0 °C - 20 °C	214.6 W/m^2	92.3 W/m^2
10 °C - 20 °C	85.9 W/m^2	36.9 W/m^2

3.2. Results of Moisture Transfer Analysis and the Assessment of Mold Risk within Panel Assemblies

Table 4 shows the results of hygrothermal analysis of both UHP-FRC and conventional panel assemblies regarding relative humidity and mold index for ten years. The results show that the relative humidity behind the insulation layer in both UHP-FRC and conventional panels remains less than 80%. However, the relative humidity on the interior side of the UHP-FRC panel assembly is slightly lower than the relative humidity on the interior side of the conventional panel assembly in all the locations. These results show that the UHP-FRC panel performs better than conventional panel even in Miami, where the relative humidity of the conventional panel on its interior side slightly passes 80% threshold. Moreover, the results for mold index show that the risk of mold growth is 0 (6 highest and 0 no risk) behind the insulation layers of the UHP-FRC panel assembly in all locations. Similar mold indexes have been obtained for the conventional panel assembly for all locations.

Table 4. Moisture behavior behind the insulation layer and maximum mold index for ten years

Relative humidity City	Orientation	Conventional panel			UHP-RFC panel		
		Interior surface		Behind insulation layer	Interior surface		Behind insulation layer
		RH (%)	Mold index	Mold index	RH (%)	Mold index	Mold index
Fairbanks	SW	26-73	0	0	22-73	0	0
Duluth	E	27-75	0	0	23-73	0	0
Helena	N	28-74	0	0	25-72	0	0
Burlington	SW	27-77	0	0	25-73	0	0
Chicago	NE	28-76	0	0	25-74	0	0
Boise	W	28-73	0	0	26-70	0	0
Albuquerque	E	22-73	0	0	26-72	0	0
San Francisco	SW	43-76	0	0	40-76	0	0
Salem McNary	S	36-76	0	0	34-74	0	0
Baltimore	NE	27-76	0	0	25-73	0	0
Memphis	S	29-75	0	0	26-73	0	0
El Paso	W	20-74	0	0	30-71	0	0
Houston	NE	34-77	0	0	32-74	0	0
Phoenix	E	17-70	0	0	26-70	0	0
Miami	SE	46-84	0	0	43-77	0	0

3.3. Results of Whole Building Energy Simulations

The outputs of building energy simulations were used to compare the energy performance of commercial buildings enhanced by UHP-FRC façade panels with the baseline commercial buildings with the conventional panels. Table 5 shows the average annual building energy saving percentages for different scenarios when the conventional panels are being replaced with the UHP-FRC panels. Based on these results, replacing the conventional panels by the UHP-FRC panels reduces the building energy consumptions in 44 scenarios out of 45; only in one scenario, the energy savings were negative. The highest energy savings (5.6%) were observed for the small office prototype building located in Fairbanks (the coldest location among all locations). On the other hand, the same small office building has the lowest energy savings (-0.1%) in San Fransico as a temperate location. Same as the small building, the medium and large office buildings had the highest energy savings in Fairbanks and lowest energy savings in San Francisco.

Table 5. The average annual building energy saving percentages by replacing the conventional façade panel with UHP-FRC façade panel

Locations Buildings	Fairbanks	Duluth	Helena	Burlington	Chicago	Boise	Albuquerque	San Francisco	Salem McNary	Baltimore	Memphis	El Paso	Houston	Phoenix	Miami
Small office	5.6	4.2	3.5	3.6	3.2	2.6	1.2	-0.1	2.4	2.2	1.4	1.0	0.8	1.5	1.1
Medium office	1.8	1.4	1.2	1.2	1.2	1.0	0.6	0.2	1.1	0.9	0.8	0.5	0.6	1.0	1.4
Large office	1.7	1.5	1.7	1.6	1.5	1.4	0.7	0.3	1.5	1.0	0.8	0.3	0.3	0.3	0.3

Based on the building energy simulation results, it can be concluded that on average the UHP-FRC façade panels perform better than conventional façade panels in cold climates than in temperate climates. The reason behind this fact is that a tighter building construction using UHP-FRC panels needs heating or cooling during the transition seasons (spring and fall) in the temperate climates. Buildings can be classified as ‘internally-dominated’ buildings, such as large office buildings, and ‘envelope-dominated’ buildings such as smaller buildings with higher surface area to volume ratio, such as small office building (Lechner, 2014). Energy use of internally-dominated buildings is mostly impacted by their internal load (e.g., people, equipment, etc.) than their envelope. This is the reason that the energy performance of the UHP-FRC panels is higher in small office buildings compared to medium and large office buildings.

4. Conclusions

The results of building energy simulations showed that buildings with UHP-FRC façade panels consume less energy than the buildings with conventional panels in almost all the scenarios (44 scenarios out of 45). Only in one scenario (small office in San Francisco), the building with the conventional panels outperform the building with the UHP-FRC façade panels. Although UHP-FRC façade systems have thicker insulation layers with higher R-value compared with the conventional panels, they do not necessarily result in building energy reduction; the energy savings of using UHP-FRC panels depend on the building type, size and also climate conditions. The energy performance assessment of innovative façade systems such as UHP-FRC panels could be misleading if the diversity of building types and climate contexts are not taken into account. On average, energy savings are higher in colder climates (e.g., Fairbanks) than those in temperate climates (e.g., San Francisco). Also, on average, buildings that are dominated by internal loads (e.g., large office buildings) seem to benefit the least from UHP-FRC. Moreover, the implementation of the UHP-FRC panel could decrease the risk of condensation and mold growth behind the insulation layer in comparison with the conventional panel. These findings contribute to the body of knowledge by showing the significant importance of context in the evaluation of innovative façade systems. It is expected that the results inform the designers about the energy performance of UHP-FRC façade panels in various building and climate contexts.

5. References

Abdou, Ossama A., Kris Murali, and Ahmed Morsi. "Thermal performance evaluation of a prefabricated fiber-reinforced plastic building envelope system." *Energy and buildings* 24.1, 1996: 77-83.

Abediniangerabi, B., Shahandashti, S. M., Bell, B., Chao, S. H., & Makhmalbaf, A. (2018). Building energy performance analysis of ultra-high-performance fiber-reinforced concrete (UHP-FRC) façade systems. *Energy and Buildings*, *174*, 262-275.

Aghdasi, Parham, Ashley E. Heid, and Shih-Ho Chao. "Developing Ultra-High-Performance Fiber-Reinforced Concrete for Large-Scale Structural Applications." *ACI Materials Journal* 113.5, 2016.

Ahlborn, Theresa, et al. "Characterization of strength and durability of ultra-high-performance concrete under variable curing conditions." *Transportation Research Record: Journal of the Transportation Research Board* 2251, 2011: 68-75.

Bell, B., Shihabeddin, L., Essari, J., Arevalo, H., & Richardson, S. "High Performance Precast Façade Panels", White paper, Link: https://static1.squarespace.com/static/5588241ce4b0562ee8fe469a/t/57a74cd7b3db2b8908f4f2ef/1470581979516/UHPC+Panel_Final+Boards_11x17+%281%29.pdf, Last Visited: 12/12/2016.

Briggs, Robert S., Robert G. Lucas, and Z. Todd Taylor. "Climate classification for building energy codes and standards: Part 2-Zone definitions, maps, and comparisons." *ASHRAE Transactions* 109 (2003): 122.

Finken, Gholam Reza, Søren Peter Bjarløv, and Ruut Hannele Peuhkuri. "Effect of façade impregnation on feasibility of capillary active thermal internal insulation for a historic dormitory–A hygrothermal simulation study." *Construction and Building Materials* 113, 2016: 202-214.

Iommi, Matteo. "The mediterranean smart adaptive wall. An experimental design of a smart and adaptive facade module for the mediterranean climate." *Energy and Buildings* 158 (2018): 1450-1460.

Kaka, V. B., and Chao, S.-H. "Investigation of Eliminating Prestress in Bridge Girders with the Use of Non-Prestressed Ultra-High-Performance Fiber-Reinforced Concrete Girders." ASCE Structures Congress, 2018. Fort Worth TX.

Karasu, A. "Building energy efficiency with climate envelopes." Contemporary Trends in the Regenerative and Sustainable Built Environment: Technical and Managerial Aspects, (2015): 115.

Lechner, Norbert. "*Heating, cooling, lighting: Sustainable design methods for architects*." John wiley & sons, 2014.

Losch, Edward D., et al. "State of the art of precast/prestressed concrete sandwich wall panels." *PCI Journal* 56.2, 2011: 131-176.

Mitchell, Robin, et al. "THERM 5/WINDOW 5 NFRC simulation manual.",2003.

Parent M. "Estimation du potentiel technico-économique d'économie d'énergie au Québec: Secteur commercial et institutionnel au tarif L" Québec, Rapport de Technosim Inc. pour Hydro-Québec, 2002.

Park, Benjamin, Wil V. Srubar III, and Moncef Krarti. "Energy performance analysis of variable thermal resistance envelopes in residential buildings." *Energy and Buildings* 103, 2015: 317-325.

Pavlík, Zbyšek, and Robert Černý. "Hygrothermal performance study of an innovative interior thermal insulation system." *Applied Thermal Engineering* 29.10,2009: 1941-1946.

Real, Sofia, et al. "Contribution of structural lightweight aggregate concrete to the reduction of thermal bridging effect in buildings." *Construction and Building Materials* 121, 2016: 460-470.

Sadineni, Suresh B., Srikanth Madala, and Robert F. Boehm. "Passive building energy savings: A review of building envelope components." *Renewable and sustainable energy reviews*, 15.8, 2011: 3617-3631.

Sailor, David J. "A green roof model for building energy simulation programs." *Energy and buildings* 40.8, 2008: 1466-1478.

Shahandashti, S. M., Abediniangerabi, B., Bell, B., & Chao, S. H. Probabilistic Building Energy Performance Analysis of Ultra-High-Performance Fiber-Reinforced Concrete (UHP-FRC) Façade System. In *Computing in Civil Engineering 2017*(pp. 223-230).

U.S. Energy Information Administration. "Independent Statistics and Analysis," 2015 August 08. Available at http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1, 2015

U.S. Department of Energy, "Energy Efficiency & Renewable Energy Office," 2016, August 08. Commercial Prototype Building Models. Available at: https://www.energycodes.gov/development/commercial/prototype_models, 2016a.

U.S. Department of Energy, "Building Technologies Office." 2016, August 08. EnergyPlus. Available at https://energyplus.net/, 2016b.

U.S. Department of Energy, "Energy Efficiency & Renewable Energy." (2018b, February 27). "Climate Zones." Available at https://energy.gov/eere/buildings/climate-zones, 2018.

Zirkelbach, D., et al. "Wufi® Pro–Manual." *Fraunhofer Institute*, 2007.