HIGH-PERFORMANCE BUILDING ENVELOPES: DESIGN METHODS FOR ENERGY EFFICIENT FACADES

Ajla Aksamija, PhD, LEED AP BD+C, CDT¹

ABSTRACT

The objective of this paper is to discuss design methods for sustainable, high-performance facades, and the necessary steps in ensuring that the environmental factors and energy-efficiency strategies are integrated with the design process. The facade is one of the most significant contributors to the energy consumption and the comfort parameters of any building. Control of physical environmental factors (heat, light, sounds) must be considered during the design process, as well as design strategies which improve occupants' comfort. High-performance facades need to block adverse external environmental effects and maintain internal comfort conditions with minimum energy consumption, and the location and climate become one of the crucial factors in selecting appropriate design strategies.

The first part of the paper identifies design methods for high-performance facades, differentiated by climate types. Then, characteristics of sustainable facades and discussion of specific design methods, such as proper treatment of different building orientations, selection of window-to-wall ratio, shading elements, and daylighting methods are presented. Selection of materials and their properties is also discussed, since material characteristics are a very important factor for sustainable facades, and design decisions relating to material properties can greatly influence their performance. The second part of the paper discusses different building performance analysis steps that can assist in the design process, such as energy modeling, daylight modeling, thermal comfort modeling, and heat transfer analysis. The appropriate strategies for incorporating analysis procedures with the design are presented, such as when and how to integrate different software tools, compatibility with BIM design authoring tools, and applications for high-performance facade designs. Finally, two case studies are presented to show how these strategies have been implemented on architectural projects.

Keywords: high-performance facades; energy-efficiency; simulations; building performance analysis tools; sustainable buildings; daylight; thermal comfort

1. CLIMATE-BASED DESIGN METHODS FOR HIGH-PERFORMANCE FACADES

High-performance sustainable facades can be defined as exterior enclosures that use the least possible amount of energy to maintain a comfortable interior environment, which promotes the health and productivity of the building's occupants (Aksamija, 2013). This means that sustainable facades are not simply barriers between interior and exterior; they are building

¹ Assistant Professor, University of Massachusetts, Amherst, MA, USA/Building Technology Researcher, Perkins+Will

systems that create comfortable spaces by actively responding to the building's external environment, and significantly reduce buildings' energy consumption.

Climate-specific guidelines must be considered during the design process of high-performing building enclosures (Oral et al., 2004). Strategies that work best in hot and arid climates are different from those that work in temperate or hot and humid regions. For most buildings, the facade affects the building's energy budget and the comfort of its occupants more than any other system. In order to provide occupants with a comfortable environment, a facade must fulfil many functions, such as providing views to the outside, resisting wind loads, supporting its own dead-load weight, allowing daylight to interior spaces, blocking unwanted solar heat gain, protecting occupants from outside noise and temperature extremes, and resisting air and water penetration (Aksamija, 2009). Basic methods for designing high-performance building facades include:

- Orienting and developing geometry and massing of the building to respond to solar position;
- Providing solar shading to control cooling loads and improve thermal comfort;
- Using natural ventilation to enhance air quality and reduce cooling loads;
- Minimizing energy used for artificial lighting and mechanical cooling and heating by optimizing exterior wall insulation and the use of daylighting.

Climate type	Design strategies for sustainable facades
Heating-dominated climates	 Solar collection and passive heating: collection of solar heat through the building envelope
	Heat storage: storage of heat in the mass of the walls
	 Heat conservation: preservation of heat within the building through improved insulation
	 Daylight: use of natural light sources and increased glazed areas of the facade, use of high-performance glass, and use of light shelves to redirect light into interior spaces
Cooling-dominated	• Solar control: protection of the facade from direct solar radiation
climates	through self-shading methods (building form) or shading devices
	• Reduction of external heat gains: protection from solar heat gain
	by infiltration (by using well-insulated opaque facade elements) or
	conduction (by using shading devices)
	 Cooling: use of natural ventilation where environmental
	characteristics and building function permit
	 Daylight: use of natural light sources while minimizing solar heat gain through use of shading devices and light shelves
Mixed climates	Solar control: protection of facade from direct solar radiation
	(shading) during warm seasons
	• Solar collection and passive heating: solar collection during cold
	seasons
	 Daylight: use of natural light sources and increased glazed areas of the facade with shading devices

TABLE 1: Facade design strategies for different climate types.

Design strategies need to consider the conditions of the climate zone to minimize their impacts and reduce energy consumption. Table 1 shows basic strategies for different climate types. Heating-dominated climates benefit from collection of solar radiation, passive heating, heat storage, improved insulation to reduce heating demand, and the use of daylighting to reduce lighting demand. In cooling-dominated climates, protection from sun and direct solar radiation becomes more important. In mixed climates, combined strategies that balance solar exposure and access to daylight must be implemented.

2. CHARACTERISTICS AND PROPERTIES OF SUSTAINABLE FACADES

What are the properties of energy-efficient, sustainable building facades? They include: (1) allowing daylight into a building; (2) preventing unwanted solar heat from entering the building; (3) storing heat within the mass of the wall; (4) preventing heat transfer through improved insulation; (5) preventing air or moisture from passing through the facade; and (6) allowing natural ventilation to cool the building's interior. These properties are highly dependent on climate, as well as a building's function, occupancy patterns, orientation, and equipment loads, as well as the facade type (Lee et al., 2002). There are essentially two types of facades:

- Opaque facades, which are primarily constructed of layers of solid materials, such as masonry, stone, precast concrete panels, metal cladding, insulation, and framing.
 Opaque facades may also include punched opening or windows.
- Glazed facades, such as curtain walls or storefront facades, which primarily consist of transparent or translucent glazing materials and metal framing components.

Physical behaviors of these two types of facade differ, since their components, materials, and construction methods are different. Opaque facades typically have more mass, greater insulation levels, and better heat retention than glazed facades. On the other hand, glazed facades usually allow more daylight to the interiors, provide better views for occupants, and impose less dead load on the building structure than opaque facades.

2.1 Orientation and Fenestration

The orientation of a building determines its exposure to sunlight. Since the angle of the earth relative to the sun varies throughout the year and the sun moves across the sky during the day, solar exposure on a facade is continually changing. Strategies for controlling solar heat gain depend on the building's orientation. As stated in the previous section, solar heat gain can benefit buildings in colder climates during winter months. In warmer climates, on the other hand, interior spaces need to be shaded from direct sunlight much of the year. The optimal orientation of the building, from the perspective of solar heat gain, balances desirable solar heat gain during winter months with solar shading during summer months. In very hot climates, solar heat gain must be kept as low as possible during the entire year, but especially during summer months. In cool climates, more balance is needed across the seasons. In winter months, solar exposure should be used to passively heat the building.

Because the passive effects of solar orientation are so significant, the orientation of the facades should be considered early in the design process. The environmental conditions and solar radiation are different and require differing responses for facades facing north, south, east, and west orientations. For example, northern and southern exposures are beneficial for daylighting, on the north because the light is indirect, and on the south because the sun is high enough in the summer to allow shading of the direct sunlight. There is usually a daylighting advantage in maximizing these exposures. On the other hand, because the sun is usually low in the east and west, facades along the eastern and western orientations should be minimized. If specific site constraints do not allow this strategy, deep vertical fins on those facades can be used to block most of the low morning and afternoon sunlight. When a building is designed to take advantage of its orientation, comfortable living and working conditions inside the building will be achieved at a relatively low consumption of energy.

Fenestration components (windows, curtain walls, clerestories) are significant elements of facade design, from both aesthetic and performance perspectives. They allow natural light to

enter interior space, but also allow heat transfer between the outside and inside. Fenestration elements affect a building's overall energy consumption, as well as its occupants' well-being, health, comfort, and productivity. When choosing fenestration materials, specific properties of glass should be considered, such as U-values, SHGC and visual transmittance. The design of the fenestration framing system is also important.

Recent developments in fenestration products use new advances in building technology to allow transparent, yet energy-efficient facades. Glazing units can be insulated using two, three or more layers of glass. The spaces between the glass layers can be filled with inert gases or aerogel insulation to lower the U-value of the unit. Low-e, reflective, or ceramic frit coatings can be applied to the glass to reduce transmission of solar heat gain. Interlayer films within laminated glass can also provide shading.

An important metric of facade's characteristics is the window-to-wall ratio (WWR). This is the proportion of glazed to opaque facade area. This ratio is a significant contributor to a facade's solar heat gain and energy consumption. In most cases, higher WWR result in greater energy consumption, since thermal resistance of even a well-insulated glazed facade is typically lower than that of an opaque facade.

For hot and warm climates, increased WWRs cause cooling loads to increase due to increased solar heat gain. For mixed and colder climates, higher WWRs also affect heating loads, especially for buildings located in cold and very cold climates. In all climate types, reducing the WWR (by increasing the amount of opaque facade relative to glazed facade) improves the energy efficiency.

2.2 Material Selection

Material selection is an important factor in designing sustainable facades. Improving thermal performance of building envelopes and minimizing thermal bridging are extremely important design strategies for sustainable facades. Thermal bridging within a wall occurs where a highly conductive material, such as a metal support, penetrates the facade's insulation layer. This can significantly affect the thermal performance of the wall, and lower its effective thermal resistance (Lawton et al., 2010). Thermal bridging can occur in all types of facades. Thermally unbroken aluminum mullions in curtain walls are highly conductive and transfer heat from the exterior to the interior, reducing the overall thermal performance of the facade.

Material selection also has an environmental impact. It is becoming increasingly important to select materials that have the least negative effect on the environment. The life-cycle assessment approach can be used to determine environmental impacts of material selection, where material contents, production methods, energy requirements, and waste are analyzed to identify the real cost of a material, reflecting the total amount of its environmental impact (ISO, 2006). Selecting materials based on the embodied energy data is also an appropriate method for considering environmental impacts. The embodied energy is the amount of energy required to extract, process, transport, install, and recycle or dispose of a material, and is commonly measured per mass or volume of the material. When comparing the embodied energy of facade systems, the measurements should be based on area instead of mass or volume, considering the embodied energy of individual components and materials of the facade.

2.3 Heat and Moisture Movement

Heat transfer through facades follows a basic principle of physics: heat flows from higher to lower temperatures. This takes place through one or more of the following processes:

- Conduction (heat flows between two facade materials in contact with each other);
- Convection (heat is conveyed by air currents within the facade);

- Radiation (heat flows as electromagnetic energy through materials and air spaces within the facade);
- Air leakage (heat is conveyed by air passing through the facade).

The rate of heat transfer through the building skin depends on the difference between the interior and exterior temperatures and the capacity of the facade to control heat flow. Factors that influence heat flow within the facade include the overall thermal resistance, material properties, and air leakage control. Design strategies for controlling heat flow include using a continuous thermal barrier (insulation layer), filling air gaps between material layers to prevent conduction, providing a continuous air barrier to prevent heat loss through air leakage, and avoiding thermal bridging.

Air leakage can affect a building's overall energy consumption, since it permits unwanted warm air to enter the building (increasing cooling loads) or warm inside air to escape to the colder outside (increasing heating loads). Exterior air can also carry moisture (as vapor) into the building envelope and the building itself, causing condensation and, potentially, mold and damaged building materials. Air leakage is never desirable, but also can never be completely prevented. Installation of air barriers reduces the movement of air through a building enclosure. Air barriers control airflow between unconditioned and conditioned spaces, and are intended to resist differences in air pressure between interior and exterior. They can be located anywhere in the building enclosure (the exterior surface, the interior surface, or somewhere in between). Air barriers must be continuous over the entire building enclosure, and be impermeable to air flow.

Vapor infiltration and moisture movement through facades are also very important design considerations for sustainable building envelopes. Since vapor is carried by air, then it follows that some vapor is inevitably entering the exterior wall. The problem occurs when the vapor-bearing air encounters a material that is colder than the air. When the air cools, its capacity for carrying vapor is reduced. If the air cools off enough, the vapor condenses into water. If the vapor condenses within the wall, the resulting water can saturate materials. That water may create an environment that promotes the growth of mold, which can have a serious effect on the building's occupants and their health. Sustainable facades are designed so that when the vapor condenses, it will happen in a location in the wall where the water can drain to the outside.

Vapor barriers reduce the movement of moisture and vapor diffusion through the building enclosure. Their placement within the wall assemble depends on the climate type. For example, in colder climates, the vapor barrier is usually placed on the inside (warm) surface of the insulation. In hot or warm climates, especially in the humid subzones, the vapor barrier is usually on the exterior side of the insulation layer. In mixed climates, there is no ready answer for placement of vapor barriers. Prevailing temperature and humidity conditions, both inside and outside the building, should be considered. There should never be two vapor barriers within a wall assembly, since this could trap moisture and not allow it to drain or evaporate.

2.4 Thermal Comfort

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE, 2004). Since it is a condition of mind, comfort is inherently based on one's experience and perception; there are large variations in physiological and psychological responses for different individuals (Arens et al., 2006). Six primary variables affect thermal comfort: air temperature, air movement, humidity, mean radiant temperature, occupants' metabolic rate, and occupants' clothing (Huizenga et al., 2006). While each of these variables can be separately measured, the human body responds to them holistically.

For naturally ventilated spaces, where occupants have some control over their environment (e.g., by opening or closing windows to alter air temperature and air movement), the ASHRAE

standard provides an optional method for determining thermally acceptable conditions (ASHRAE, 2004). Indoor operating temperatures can be adjusted, depending on the mean monthly outdoor temperatures, while still maintaining acceptable comfort conditions. These criteria can also be used for buildings with mixed-mode ventilation systems (i.e., natural ventilation, or facade openings, combined with HVAC systems). Mixed-mode buildings can be naturally ventilated with outside air through facade openings when environmental and climatic conditions are favorable and mechanically ventilated when conditions are not favorable. The goal of well-designed mixed-mode buildings is to reduce or eliminate energy consumption by fans and cooling systems when conditions allow for natural ventilation.

Of all the facade elements, windows have the largest thermal fluctuations. Windows are usually the coldest interior surfaces in cold weather and the warmest interior surfaces in warm weather. This is the case even for windows with high-performance glazing and thermally broken frames. As a result, facades with high WWRs are more likely to affect the thermal comfort of occupants than those with low WWRs. This effect increases as occupants get closer to the window, and also depends on how active the occupants are. The optimal WWR should be based on the floor plan of a space, the occupants' positions in the space, and the types of occupant activities. Smaller WWRs should be used for spaces where occupants are typically close to the windows, especially for the south-oriented facades.

The choice of facade glazing materials also influences occupants' thermal comfort (Huizenga et al., 2006). The effects are different for summer and winter. During winter, the thermal comfort effect is largely driven by inside window surface temperature, which is usually colder than the room it faces. During the summer, thermal comfort is driven by the combination of the inside surface temperature of the glass and the transmitted solar radiation through the glass. These in turn are significantly influenced by the construction of the glazing units, the material properties of the glass, and the effectiveness of shading elements used with the window.

2.5 Daylight

When considering daylight and visual comfort, designers need to consider illumination levels, daylight distribution, and protection against direct sunlight and glare. Integration of building systems is also important, since facades, lighting, shading elements, HVAC systems, and building controls need to function together to have the largest effect on building performance. For example, spaces that use natural daylight for perimeter zones and control artificial lighting with photo-sensors and dimmers reduce the cooling loads for the HVAC system and, most likely, the sizes of mechanical equipment and ductwork.

The orientation and WWR of a building influence the availability of natural light for interior spaces. Analyzing daylight availability during the different seasons is an important part of the design process for high-performance sustainable facades. The primary energy-related design objective of a daylighting system is to provide as much usable daylight as deeply into a building's interior as possible. The secondary objective of daylighting is energy conservation. Sustainable strategies for improving natural light levels provide ways of increasing that depth without increasing the amount of glazing.

Light shelves have been successfully and economically used to expand the daylighting zone (Ruck et al., 2000). Light shelves are horizontal fins mounted to the inside of the window framing. During winter months, when the height of the sun is low, sunlight can pass above the light shelf to provide radiant warmth to the interior spaces. During summer months, the direct sunlight is blocked by the light shelf, but it is redirected off the top surface of the light shelf to hit the ceiling of the space, and then bounces again deep within the space. This effectively increases the daylighting zone using indirect light with minimal or no direct sunlight penetrating

the building. Translucent glazing materials can be used to provide filtered, uniform, and glarefree daylight. By combining transparent vision glass at eye level with translucent glass above and below, designers can enhance the daylighting while giving occupants views to the outside.

3. BUILDING PERFORMANCE ANALYSIS PROCEDURES

Building performance simulations are an integral part of the design process for energy efficient and high-performance buildings, since they help in investigating design options and assess the environmental and energy impacts of design decisions (Aksamija, 2009a; Aksamija, 2010; Augenbroe et al., 2004). They are an essential part of the design process for sustainable, high-performance building facades. Quantifiable predictions during the different stages of the design process help establish metrics that can be used to measure improvements by using different design strategies. In order to evaluate and optimize the building performance, different analysis cycles should be part of an integrated design process (Punjabi & Miranda, 2005).



FIGURE 1: Framework for incorporating building performance analysis procedures with design of high-performance building envelopes.

Figure 1 shows the basic types of performance analysis in relation to the project stages, particularly focusing on building envelope design. The top part of the diagram shows the impact of decisions on actual building performance, and relationships to project stages. As can be seen, as early as programming phase the analysis should focus on the contextual aspects, such as climate information, orientation, and building massing. Then at conceptual and schematic phases, the analysis observes the whole sun shading method proposed for the facade in alignment to overshadowing of surrounding buildings. Generally, an iterative cycle of different design options of sun shades should be analyzed, as well as daylighting studies. The decisions here are of high impact on the design because they influence the exterior design character of the project, potential energy use reduction, and affect the comfort levels inside the spaces. What is important to highlight is that such type of analysis takes place mostly during design development and less during construction documentation phase.

It has become important that designers evaluate building energy performance at early and schematic project phases before a detailed energy model is produced. This saves the project from drastic changes due to misguided energy goals. However, building performance assessment is a long process, and is often performed by two primary methods. The first method is the energy analysis part, whereby it follows two stages and each is utilizing the appropriate tools. Those are:

- Understanding energy target goals: the aim is to establish early in the project some meaningful energy performance targets in order to assess against the different design schemes. With this, early design characteristics and decisions are understood such as: the site, building orientation, climatic conditions, shadow ranges basic solar exposure and its directionality, and passive strategies based on the location.
- 2. Design solutions and optimization: occur when the project progresses into design development phase. For example, the building envelope undergoes cycles of performance analysis based on the exterior skin configurations. In this approach, different design options can be tested utilizing a more detailed 3D prototype model, and these following analysis types can be performed: façade solar exposure analysis to determine total solar radiation, shadow analysis, daylight simulations, and breakdown of energy gains (direct solar, internal gains and exterior wall gains).

Energy modeling is the second method and it focuses primarily on sizing and selection of mechanical equipment and prediction of annual energy consumption through the "whole building" approach.

The simulations and performance analysis tools can be grouped into BIM-based or non-BIM based software programs. There are varieties of tools and simulation programs with different modeling capabilities. Crawley at al. published a study that compared capabilities of twenty different building performance simulation programs (BLAST, BSim, DeSTm DOE-2.1E, Ecotect, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQuest, ESP-r, IDA ICE, IES VE, HAP, HEED, PowerDomus, Sunrel, TAS, TRACE, TRYNSYS) (2006).

But, how are these tools used in architectural practices? A recently conducted survey investigated utilization of building performance tools in architectural practice, particularly comparing these following simulation programs: ECOTECT, HEED, Energy 10, Design Builder, eQuest, DOE-2, Green Building Studio, IES VE, EnergyPlus and EnergyPlus-SketchUp plug-in OpenStudio (Attia et al., 2009). With 249 responses, the survey ranked utilization of tools and investigated requirements for potential future improvements of these applications. Findings show that Ecotect is currently most widely used (156 users), followed by eQuest (123 users), EnergyPlus-SketchUp (81 users) and EnergyPlus (81 users), IES VE (60 users), Energy 10 (57 users), DOE-2 (48 users), HEED (45 users) and Green Building Studio (27 users). The survey also revealed that different tools tend to be used during different

stages of the design process. For example, Green Building Studio, Energy 10, HEED, Design Builder and Ecotect are applicable during conceptual and schematic design phases. IES VE and eQuest are applicable in schematic and design development phases, while EnergyPlus is mainly applicable during the design development. However, compatibility with BIM-based design software is limited to a few applications, mainly Green Building Studio, Ecotect and IES VE.

Best practices for data exchange between BIM and environmental analysis software depend on the analysis objectives and what type of data is needed. For example, for determination of building massing that minimizes solar exposure or incident solar exposure on the facade, data exchange through DXF file format is adequate. For these types of studies, geometric properties of the building massing or component under analysis (for example, part of the facade with shading devices) are sufficient.

For other types of studies, such as daylight or thermal analysis, enriched information about interior spatial organization, material properties and properties of shading surfaces is needed. Therefore information stored in "design" BIM needs to be exported as "analysis" BIM. For example, Ecotect analysis software is designed to be used during the early stages of the design process and can be effectively used for a variety of analysis functions, such as shadow analysis, shading, solar exposure studies, lighting and daylight studies. Data exchange between BIM design authoring software Revit and Ecotect can be performed using Green Building XML (gbXML) format, a schema specifically developed to facilitate transfer of building properties stored in BIM to analysis tools. The basic structure of gbXML consists of elements such as rooms, walls, floors, ceilings, shading surfaces and windows, which inherit properties embedded in the model (actual numeric values) and transfer to analysis applications.

Simulation	Energy	Energy	Heat transfer	Combined heat and	Daylight	Thermal comfort	BIM-compatible
tool	analysis	modeling	analysis	moisture analysis	analysis	analysis	
Ecotect	+				+		Yes
Radiance					+		
COMFEN/ EnergyPlus	+	+					
eQuest	+	+					
Green Building Studio	+	+					Yes
CBE Thermal Comfort Model						+	
WINDOW			+				
THERM			+				
WUFI				+			

FIGURE 2: Building performance simulation software programs and their applicability for facade design.

Figure 2 provides an overview of applicable simulation programs for the design of sustainable, high-performance building facades. Since there is not a single simulation program that can address all aspects and design questions that are posed during the design of high-performance facades, typically several different programs must be used to investigate properties and behavior of facade systems. For example, energy analysis and modeling, heat transfer analysis, combined heat and moisture analysis, daylight analysis, and thermal comfort analysis are the essential parts of the design process for high-performance facades. The figure shows which applications are suitable for these types of performance simulations, and their applicability for specific design aspects.

4. CASE STUDIES

4.1 Optimization of Window-to-Wall Ratio for Different Facade Orientations

This case study is used to illustrate how to optimize WWR for different facade orientations. The building is a middle school, located in a warm climate (Dallas, Texas). It is oriented in the east-west direction to limit its east and west exposures. The classrooms are grouped along the north orientation of the building, since these spaces have a consistent energy demand. This orientation also minimizes cooling loads by protecting the classrooms from the harsh south, east, and west sun exposure. The north facade's WWR of 70% takes advantage of the available daylight and provides excellent views to the outside. The facade at the second and third levels is a two-story curtain wall with clear and colored glazing (Figure 3). At the ground level is a brick cavity wall with metal framing, punctuated by a series of long strip windows, seen in Figure 4.



FIGURE 3: Section and partial elevation of the north facade.



FIGURE 4: North facade.

Large-volume instructional spaces and other program spaces that require minimal natural light are located along the south facade. The WWR for this facade is 30%. Several exterior wall systems are used—brick cavity wall with metal framing, metal panels, aluminum curtain wall, storefront facade, and punched windows. A deep roof overhang shades the facade from the south sun (Figure 5). The east and west facades consist primarily of brick cavity wall. The openings in these facades are kept to a minimum, with a 0% WWR on the east facade and a 10% WWR on the west facade.



FIGURE 5: South facade.

4.2 Optimization of Window-to-Wall Ratio to Balance Solar Heat Gain and Daylight

This case study is used to illustrate how to optimize WWR to reduce solar heat gain through the facade, without negatively affecting the daylight. The building is a higher-education building located in very hot and humid climate (Miami, Florida). The building's program includes classrooms, student support and administrative spaces.



FIGURE 6: Rendering of the south facade.

The south facade is composed of thin-shell precast concrete panels, with intricate patterning of windows (Figure 6). The sizes and positions of windows were determined by daylighting studies (Figure 7). Thin-shell precast concrete panels consist of roughly 50 mm (2 in.) of concrete cast on to light-gauge cold-formed steel framing, seen in Figure 8.



FIGURE 7: Daylight study used to determine the window pattern in the precast concrete panels.



1 Thin-shell precast concrete panel (smooth finish)

- 2 Foam insulation
- 3 Glazing
- 4 Thin-shell precast concrete panel (board-formed finish)
- 5 Concrete column

FIGURE 8: Exterior wall section and partial elevation of the south facade.

The concrete provides durability and the desired finished look of the facade. The steel studs provide the structural support for the thin shell precast concrete panels. The resulting panels are low in weight compared with standard precast panels, reducing structural frame, transportation

and installation costs (Figures 9a and 9b). Two finishes are used for the panels—smooth finish to match the structural columns and board formed texture on the ground level facade. To improve the thermal performance of the facade, foam insulation is embedded within the thin shell concrete precast panels.



FIGURES 9a and 9b: Installation of the precast concrete panels.

CONCLUSION

All facades create barriers between the exterior and interior environment, providing building occupants with thermally, visually, and acoustically comfortable spaces. Sustainable and high-performance facades must do more; specifically they must allow optimal levels of comfort using the least amount of energy. To achieve this high performance, designers need to consider many variables—climate and climate-based design approaches, thermal performance, daylighting, solar shading, glare, moisture transport, materials and their environmental impact, etc.

This article discussed design strategies for high-performance facades, relationships between building simulations and design process, and how performance predictions can assist in identifying strategies for reducing energy consumption and improving building performance. The first part of the article discussed climate-based design strategies, identifying basic design approaches for different climate types, as well as properties and characteristics of sustainable, high-performing facades. Then, building performance analysis procedures were discussed in detail, with emphasis on building facade design. It is essential that quantifiable predictions are integrated with the design process, including energy modeling and analysis, heat transfer analysis, combined heat and moisture analysis, daylight analysis, and thermal comfort analysis. Lastly, two case studies were discussed to illustrate how these design strategies have been used on architectural projects.

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