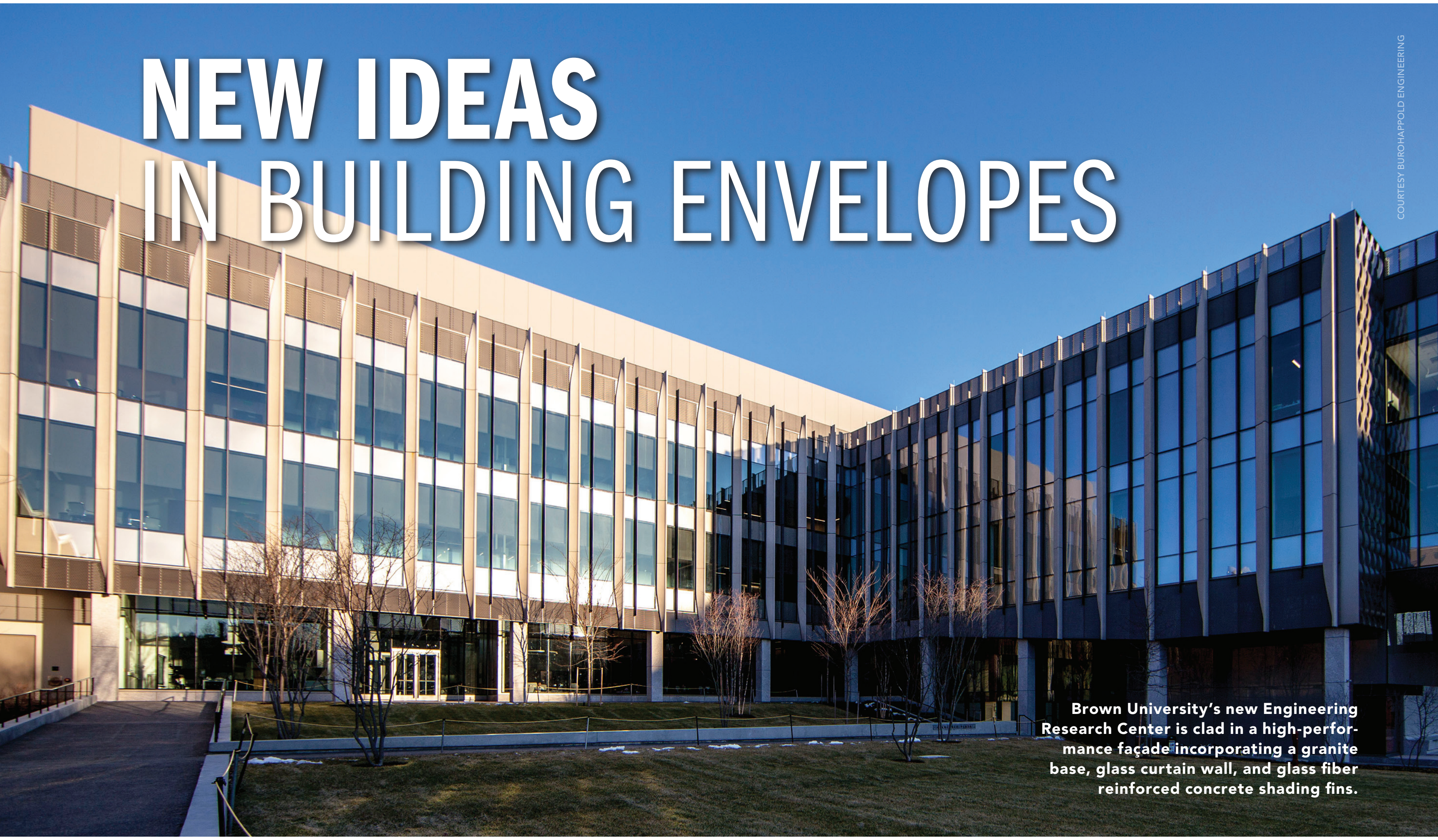
By John Ivanoff, Associate Principal, BuroHappold Engineering

NEW IDEAS IN BUILDING ENVELOPES



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Brown University's new Engineering Research Center is clad in a high-performance façade incorporating a granite base, glass curtain wall, and glass fiber reinforced concrete shading fins.

LEARNING OBJECTIVES

After reading this article, you should be able to:

- **LIST insights into the requirements for effective façade design, including climate, solar orientation, energy-use profile, and interior occupancies and preferences.**
- **DESCRIBE the competing needs of energy conservation and occupant experience, and how they can be resolved.**
- **DISCUSS facility operational requirements and material choices, and the creative strategies developed for façade engineering to enclose such occupancies.**
- **APPLY project team experiences in high-performing building design and the approaches used for integrated design and integrated project delivery.**

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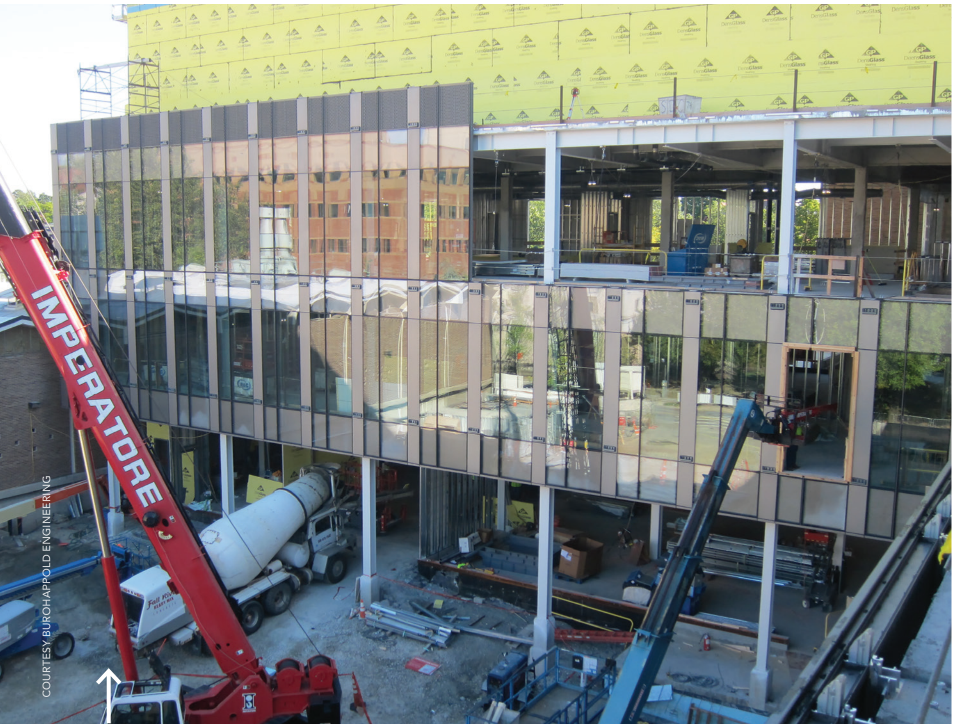
Designing and constructing the most durable and energy-efficient building enclosures requires careful integration of materials and assemblies—as well as integration of the various disciplines on the project team. This is especially true when multiple façade materials are selected to complete an exterior design scheme—metal, glass, stucco, brick, terra cotta, and the like—which bring with them a host of issues in constructability and combined performance.

The basic determinants of optimal enclosure solutions begin with considerations of climatic zone, site characteristics, orientation of the building massing and window-to-wall ratio. Annual exposure to precipitation, wind, and other loading helps inform materiality and detailing choices. Of greatest importance in most cases are the intended uses and occupancies—sometimes referred to in aggregate as interior climate class but better known to end-users as attractiveness, comfort, daylighting, views, and glare control. The broad concept of comfort includes such factors as visual environment, protection from air infiltration and draftiness, and providing even, effective thermal performance throughout the occupied spaces.

On top of these challenges, the project team must develop the



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The engineering labs employ a metal decking with hangers and acoustic roof decks to provide versatile setups as well as sound isolation, vertical and horizontal load resistance, and a means of affixing piping, ducts, and other utilities.

design concept and built solution based on the structure's energy profile: Is it dominated by enclosure loads impacting on the skin, as with many multifamily facilities? Or do internal loads constitute the major energy draw, as in large retail complexes or university laboratories? Depending on the answer, the project team brings into play various ventilation and passive-solar strategies as well as fenestration and shading combinations depending on each façade's solar orientation and interior uses. Where internal loads predominate, careful integration of the envelope design with mechanical, electrical, and plumbing systems is essential to high-performance, highly sustainable solutions.

A third order of integration is the aesthetic and functional interplay of the façades' various materials, assemblies and components. While the all-glass curtain wall continues to appear in many office and residential towers, more so today's project teams are weaving together striking, highly performative enclosures with finely tuned window-to-wall (WWR) ratios and carefully composed blends of multiple façade materials including metal, glass, terra cotta, and glass fiber reinforced concrete (GFRC). These solutions challenge the team to ensure the various elements are compatible—not only mechanically at their joints and terminations, but also in their combined contribution to performative continuity and lasting, proper management of all critical control functions.

OBTAINING POSITIVE FEEDBACK

Of the control functions in consideration, experienced project teams can list a few that dominate enclosure success, but proper engineering of moisture/air movement and thermal function tops the list. Assembly U-value—the measure of heat transmission through a building element, where lower is generally better—is a perennial indicator of effective integration. The team must also optimize solar heat gain, visible light transmission, and overillumination or glare. Last—or first, from the end-user's point of view—is the control function of meeting interior productivity and comfort needs of the occupants.

On a conceptual level, successful project teams see the challenge this way: The best façade designs result from a simple feedback loop of two inputs—energy conservation and generation on the one hand, and occupant experience on the other. These two inputs are sometimes in tension, but at other times they are happily aligned.

The variables inform each other in many ways, too. On the energy side, project teams seek optimized thermal transfer and the best possible solar gains. The ideal WWRs and the potential for integrating photovoltaic systems increase the energy benefits.

On the occupant side, the effectiveness of façade design is measured by thermal comfort, the availability of pleasant views and useful daylight, and the reduction of glare. As borne out by post-occupancy user surveys, occupant control of illumination and ventilation are tied closely to enjoyment. And then there's the x-factor of aesthetics—occupants know it (and appreciate it) when they see it.

One could see these two inputs—energy and occupant—as always in conflict with each other. Recent experience shows, however, that the best façade design solutions serve both aspects by means of the integrated and iterative design development.

DEALING WITH OCCUPANCY LOADS

In some building types, such as hospitals and scientific research buildings, façade design has limited relative impact on overall energy use when compared to ventilation loads from labs. This was the case for Brown University's Engineering Research Center in Providence, R.I. Studies showed ventilation would account for 56% of peak cooling load, regardless of façade design. Equipment loads added 19% of the peak cooling needs, followed by people, who added only 2% of cooling load from anticipated body heat and respiration.

What the project team can control is about a fifth (19%) of the cooling load: solar gain (9%), electric lighting (5%), and external conduction (about 5%). This is an important fifth. Moreover, that portion comprises about twice as much energy-conservation potential as is available under peak heating load conditions. For peak heating, a staggering 83% of the load is due to lab ventilation and makeup air. About 13% of the load is due to external conduction, and just 4% is due to air infiltration.

What's the takeaway? Façade design has a more significant impact on occupant comfort and peak cooling loads—so that's where the project team should concentrate its effort and expect the most benefit.

Another takeaway is the importance of indoor climate class. Unlike an industrial or warehouse facility, laboratories and healthcare buildings must rigorously control environmental loads including air pressure, vapor ingress, and temperature gain or loss. Engineering of the narrow façade layers around a clean room, for example, must create high-performance controls that adequately resist variations in pressure and temperature. These environmental stressors increase with the indoor climate class, according to building scientist Joseph Lstiburek, requiring careful specification of materials and details that provide continuity and resilience so that the end-user benefits from effective passive control of the indoor environment.

CHOOSING THE RIGHT MATERIALS

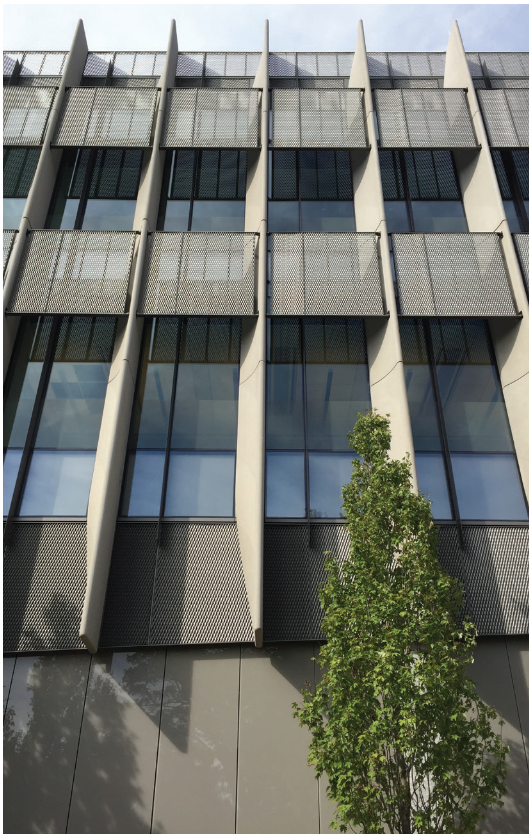
Depending on the interior uses, varying levels of transparency and opacity are needed. Solutions include window and curtain walls designed to control temperature gain or loss as well as solid structures engineered to be lightweight or translucent, or both. The testing, design, and integration of these materials can contribute to high-performance, resilient enclosures.

For a new, 14-story medical and graduate education building at Columbia University, the Roy and Diana Vagelos Education Center (see sidebar), the project team integrated state-of-the-art classrooms with a medical simulation center, auditorium, collaborative study areas, and outdoor terraces. The project reinvents the conventional layout of a stacked floor plate by creating a study cascade comprised of a series of social and study areas connected by a continuous stair on the building's southern side. To optimize transparency at this end of the building, a glass fin structure with high-performance glass was used. In developing the façade system with DS+R, Gensler, and the façade contractor Gartner, a floor-to-ceiling glass fin system with a gasket cassette assembly provides secondary drainage. The structural glass façade is set perpendicular to the enclosure at each vertical line of the glass grid.

The optimized transparency viewed from the outside and the openness of the façade let students witness interactions among classmates and enjoy impromptu meetings and informal collaborations. Yet the building's geometry presented challenges when used in varying heights across long, multistory vertical glass spans. The glass fins needed consistent widths and heights to meet the project's aesthetic vision while also meeting structural requirements.

BuroHappold modeled the glass system using the finite element analysis program SJ MEPLA accounting for maximum wind loading to determine anticipated deflection and tensile glazing stresses, including under an impact load. The resulting system's three-ply glass uses an ionoplast interlayer to improve post-breakage safety and allow greater fin spans. The glass fins are connected at the top and bottom with custom metal brackets which transfer the loads to the base building and also accommodate movement. At locations where the spans reached over 20 feet, splice connections allow longer fins spanning double-height spaces—while still maintaining transparency. The custom glass fin system was tested in Germany under a full-performance mockup regimen prior to installation.

On a separate track, the project team modeled the daylight and annual solar gain for the façades containing offices and classrooms to help determine the density of glass fritting required to ensure the occupants' thermal comfort. A vertical stripe frit is applied on the first surface of the glass for about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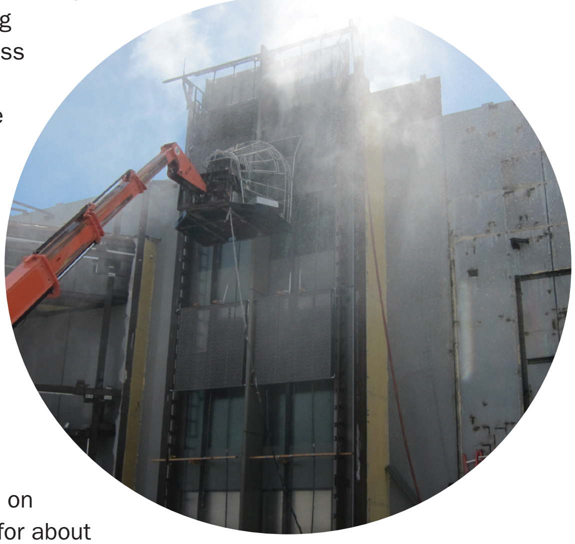
Above, engineering and research occupancies primarily use energy for ventilation—about 56% of peak cooling load—regardless of façade design. Below, mockups and factory and field inspections are essential.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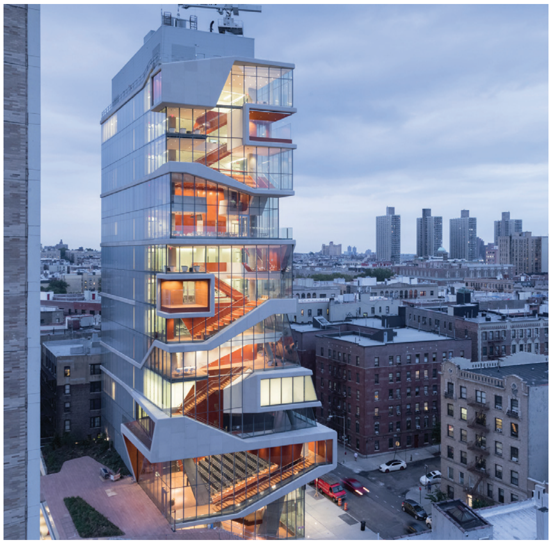
two-thirds of the façade. In addition, BuroHappold recommended using custom-cast sculptural slab covers of glass fiber reinforced concrete (GFRC) on the exposed areas of the primary structure. Rather than exposed concrete or precast, the GFRC covers create a rainscreen system which allows for continuous insulation at all opaque locations. This unique solution was preferred by the design team because of its strong, lightweight, and sustainable features, as well as its architectural flexibility.

For Brown University's Engineering Research Center, the high-performance façade incorporates a granite base, glass curtain wall, and GFRC shading fins. While the Columbia University project employs the GFRC elements primarily for aesthetics and to conceal the folded concrete slabs, the Brown University research structure presents vertical GFRC fins that are highly performative, providing carefully tuned shading based on the seasonal angle of solar incidence and interior use needs.

Together, these elements balance sustainability and occupant comfort, decreasing energy demand while providing generous daylight and views. The high-performance façade alters its composition based on each elevation's needs. The south-facing façade, for example, provides an additional element to assist in controlling solar heat gain and glare: the deep GFRC fins and aluminum mesh screen and fritted glass. The architects at KieranTimberlake and BuroHappold's integrated engineering team—including experts in structural, MEP, façades, lighting design, and energy modeling—collaborated with university researchers, Shawmut Construction, United Architectural Metals, and Massey Glass in a process that allowed for an integrated, highly collaborative design and construction process.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The Roy and Diana Vagelos Education Center, where BuroHappold Engineering recommended custom-cast GFRC slab covers for exposed structural areas to create a lightweight rainscreen with continuous insulation.

Structural Glass and Lightweight Concrete: Paradoxes That Perform

FOR THE 100,000-SF Roy and Diana Vagelos Education Center, BuroHappold Engineering worked with the architects Diller Scofidio + Renfro and Gensler to engineer a high-performance education center enclosure. The high-rise form of this academic tower, with its bilateral design and complex geometrical façade, revisits the conventional layout of a stacked-floor construction by pairing traditional classrooms and laboratory spaces with a "study cascade" design—a series of social and quiet work areas distributed across oversized landings off an exposed staircase.

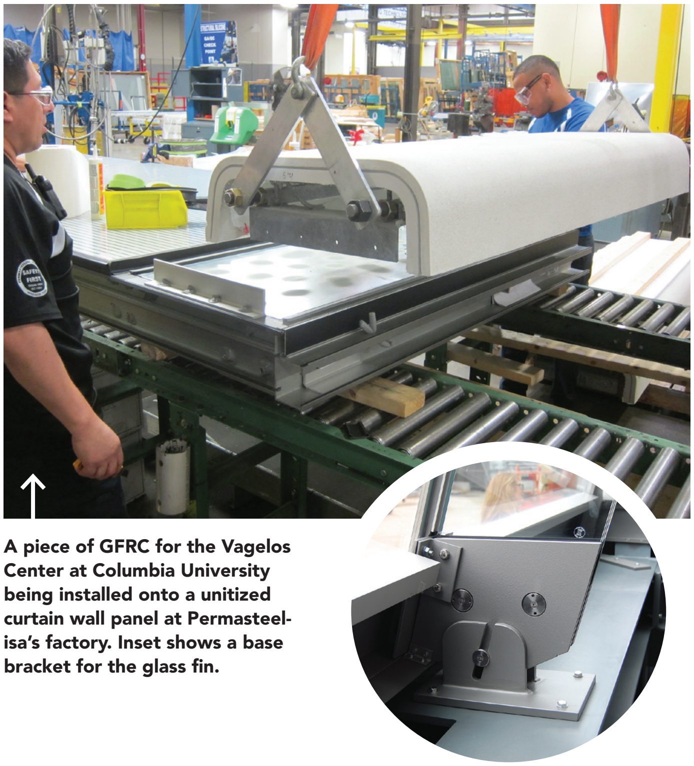
This novel layout posed an interesting challenge for the façade engineering team, with the more traditional space distributions located on back two-thirds of the building and the cascading, interwoven study zones on the building's south side. The project team decided to enclose the varied common areas with a glass curtain wall to optimize transparency and campus engagement. The curtain wall uses custom-engineered glass fin mullions, enabling the glass to be frameless and highly transparent, flooding the space with daylight.

Delivering this frameless glass façade was particularly challenging due to the building's long, multistory vertical glass spans. The high-performance curtain wall responds to the changing seasons and time of day, controlling heat gain and in turn reducing energy use.

To achieve an architecturally pleasing façade that was in line with the existing buildings on campus, the façade engineering team recommended custom-cast, sculptural GFRC slab covers instead of traditional concrete on the exposed areas of the structure. The strong, lightweight, and sustainable aspects of the slab covers—as well as their inherent architectural flexibility—made them an innovative and highly effective choice for this project.

Shaped by modeling of annual solar gain and loading on the long-span structural glass system, the team fine-tuned the façade geometry to craft an enclosure form that responds directly to the changing seasons and time of day. Engineered to introduce natural light and preserve or eliminate heat gain, the enclosure dramatically reduces energy use.

To complement the local campus context and nearby buildings—and to maintain architectural design consistency—the northern curtain wall enclosures have a ceramic frit—the baked-on ceramic coating fired into the outermost glass surfaces at high temperature. The process imbues the glass with a muted, winsome quality as it also powerfully optimizes solar heat gain and interior daylight quality.



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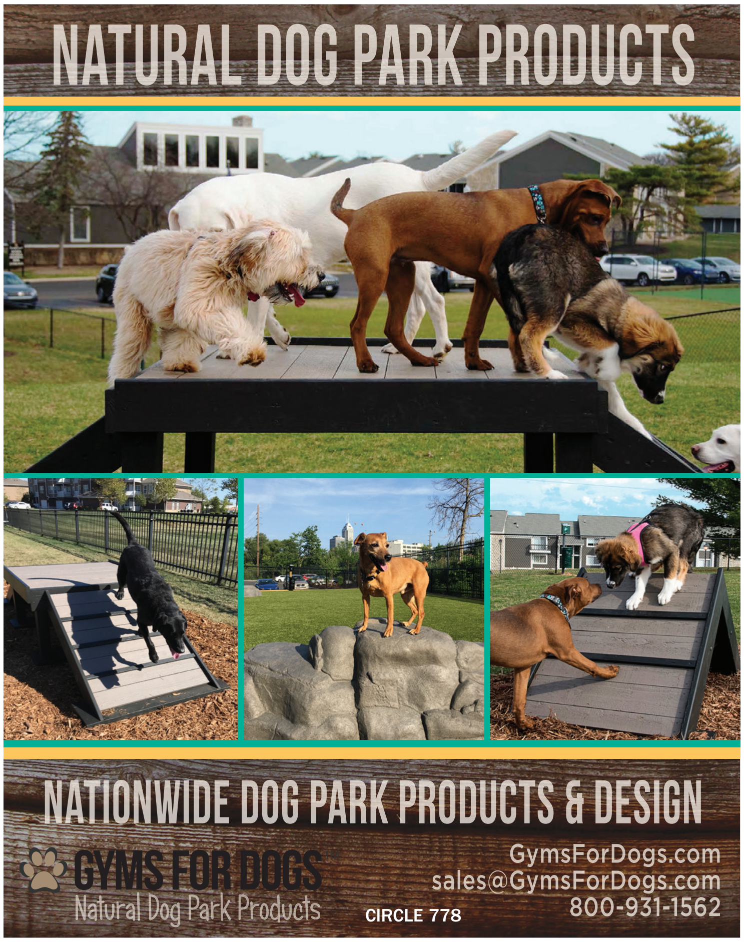
A piece of GFRC for the Vagelos Center at Columbia University being installed onto a unitized curtain wall panel at Permasteelisa's factory. Inset shows a base bracket for the glass fin.

During the development of the GFRC fins, alternate materials were evaluated, such as precast concrete and ultra-high-performance concrete, to determine which would be sympathetic to the masonry palette of surrounding campus buildings. GFRC was determined to be the preferred material choice due to its light weight, surface appearance, and ability to achieve complex geometries with the use of molds.

The project team worked with the GFRC manufacturer and façade contractor to detail the GFRC fins with integrated, formed ribs. To minimize the extent of subframing and brackets required to support the cladding, an anchorage system was integrated into the curtain wall to allow the fins to hang off the unitized façade. Integrating these systems, the GFRC fins had to take into account the subdivision and consequent position of the joints in the unitized façade system. This helped simplify the management of movements and tolerances, the size of the joints, and the design of the brackets. It also simplified the installation of GFRC fins onto the façade, reducing the duration of construction.

A PLACE FOR ENGINEERING INNOVATION

The Engineering Research Center is conceived as an 81,330-sf vessel for microelectronics and bio cleanrooms and highly flexible modular research labs flanked by flexible, loftlike workspaces.



The university envisioned this new center wrapped in glazing to maximize daylight and views into collaborative work/conference areas. Yet the glass needed to be moderated to meet energy-conservation and generation goals as well as to create an enticing occupant experience.

For energy-conservation purposes, it was important to study optimized thermal and solar transfer, optimized WWRs, and opportunities to integrate photovoltaic systems. In early studies, the BuroHappold team found that façade design had limited impact on overall energy use when compared to the ventilation loads from labs—though it had a more significant impact on occupant comfort and peak cooling loads.

The project team elected to make this project among the first institutional labs in the U.S. to use an integrated project delivery model. The approach worked well: The center was completed and occupied three months ahead of schedule—and the façade was found to perform as intended—in large part due to the IPD approach and the delivery innovations it fostered.

IPD also helped address the cost and complexity of reconfiguring laboratories as staff, technologies, and projects evolve. In response, the Engineering Research Center labs combine large and open modular layouts with innovative, dovetail composite structural decks and ceiling-mounted infrastructure that allow researchers to reconfigure their spaces themselves.

Researchers and graduate students working on similarly focused research projects are grouped together in the open, high-ceilinged workstations flanking the labs. The labs and collaboration zones are designed to control daylight and views as required by their specific programs, while gradient-fritted glass partitions in offices and workspaces offer privacy without sacrificing views or natural light.

Particularly important to Brown University's lab requirements were acoustic insulation and the means of affixing piping, ducts, and other mechanical and utility components. The team proposed metal decking with hangers that could be placed continuously across the ceiling, and installed as needed, to provide a versatile ceiling that was aesthetically pleasing and structurally capable of carrying all the MEP equipment required by the labs.

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The project team elected to make this project among the first institutional labs in the nation to use an integrated project delivery model. In this multiparty contract, the project owner, designers, contractors, and key subcontractors sign on to be mutually responsible for all facets of design, execution, and stakeholder engagement. The approach worked well: The center was completed and occupied three months ahead of schedule—and the façade was found to perform as intended—in large part due to the IPD approach and the delivery innovations it fostered.

IPD also helped address another major concern: the cost and complexity of reconfiguring laboratories as staff, technologies, and projects evolve. In response, the Engineering Research Center labs combine large and open modular layouts with innovative, dovetail composite structural decks and ceiling-mounted infrastructure that allow researchers to reconfigure their spaces themselves. Researchers and graduate students working on similarly focused research projects are grouped together in the open, high-ceilinged workstations flanking the labs. Both the labs and collaboration zones are designed to optimize or limit daylight and views as required by their specific programs, while gradient fritted glass partitions in offices and workspaces offer privacy without sacrificing views or natural light.

Particularly important when it came to designing the laboratories was meeting the Brown University School of Engineering's lab requirements of acoustic insulation and a means of affixing piping, ducts and other mechanical and utility components. BuroHappold proposed metal decking with hangers that could be placed continuously across the ceiling, and installed as needed, to provide a versatile ceiling that was aesthetically pleasing and structurally capable of carrying all the MEP equipment required by the labs. And to satisfy another important need for labs—soundproofing—acoustic roof decks proposed a cost-effective method for reducing noise and reverberation while maintaining adequate vertical and horizontal load resistance.

Key goals of the laboratory designs included flexibility, interior transparency, daylight and as

Cooling Off in the Arctic

FOR THE ANAHEIM Regional Transportation Intermodal Center, known as ARTIC, the project team led by project architect HOK set an ambitious design goal of achieving a 30% reduction in energy and water use. In addition to designing on-site renewable energy and greywater recycling programs, the team employed a building envelope of ethylene tetrafluoroethylene (ETFE) pillows—air cushions—consisting of two or more layers of foil that contribute to this highly insulating transparent material one-tenth the weight of glass. The ETFE panels are fritted so that daylight and solar gain can be controlled and used efficiently, reducing the building's overall carbon footprint. The cushions themselves have good thermal insulation due to their ability to trap air.

The heat conductivity of air is quite low if there is lack of movement. Air trapped between the ETFE foils limit convection movement, thus acting as an insulator and providing the system with reltively low thermal transmittance and good U-value.

In transparent atrium spaces, solar radiation is a big contributor to total cooling loads and may have an adverse effect on thermal comfort. In order to evaluate its intensity in this atrium space, BuroHappold employed a solar radiation study and performed computational fluid dynamics modeling to rationalize the MEP system with the complex atrium geometry and simulate the complex interactions of daylight and lighting and the ultimate impacts on energy use. The analysis also determined that fritting was needed on the foil surface to reduce solar gain while retaining translucency. By varying the percentage of coverage and density of the frit, the energy transmission can be altered.

During the development of the ETFE roof geometry, the design team developed custom computational scripts to assist in accurate fabrication of the ETFE shapes and the locating of anchor points and clamps. Due to the nonlinear load-bearing behavior of the ETFE foil, the engineers used nonlinear, three-dimensional calculations based on the finite-element method, which helped confirm the assumed reaction forces.

much openness as possible. To couple dedicated dry work areas adjacent to each technical laboratory suite, the project team developed a laminated floor plate concept that creates layers of wet laboratories, dry work areas, and building circulation within each building wing. The wet lab zones, designed using a comprehensive core-and-shell fit-out concept, assure the future adaptability of each laboratory zone. The fit-out designs use a "kit of parts" strategy that includes all MEP, architectural, and casework systems. These casework systems include fixed casework, which is typically used at perimeter locations, along with mobile casework, mobile cabinets, overhead utility drops, fume hoods, and related accessories. This kit-of-parts concept has been replicated for additional fit-outs in the research center.

FIELD WORK

To successfully deliver a custom façade system, a team of specialists employs their extensive knowledge to perform a robust analysis of the façade materials and their geometry for feasibility, serviceability and adherence to the architect's vision. Mockups, factory and field inspections have become essential to effectively deliver high-performance, durable façade systems. This is especially true when sustainability, occupant comfort and high performance are project goals.

In addition to identifying construction challenges, material interface and compatibility issues, and sequencing and integration solutions for the impacted building trades, façade mockups are reliable ways to spot and resolve performance issues before certain details are executed throughout the project during the construction phase. Typical approaches include laboratory, field, and in-situ mockups. Relevant standards and testing protocols include the AAMA and ASTM standards, including methods for determining resistance to water penetration, air leakage and other quality assurance considerations in metal curtain walls, storefronts, and sloped glazing assemblies.

The mockup tests can be customized to address specific project needs and owner concerns about longevity, resiliency and maintainability. For example, some building teams will perform additional testing such as NFPA-285 and IGU testing confirming solar heat gain and VLT levels, confirming the accuracy of computer modeling. In other cases when a full performance mock-up is not needed the project team will rely on field testing AAMA 501.2 nozzle testing or AAMA 503-14 chamber test might be performed to test perimeter seals and interfaces to ensure the workmanship in the field. The mockup can also verify the performance of the assembly's drainage capabilities through the nozzle test, which is typically less expensive than comparable chamber testing.

For a project with a custom glass and aluminum curtain wall system with integrated GFRC rainscreen panels—as for the Columbia University education center—a full-scale laboratory performance mock-up prior to fabrication allows for a range of testing including:

- air infiltration (ASTM E283-04)
- static pressure water resistance (ASTM E331)
- dynamic pressure water resistance (AAMA 501.1)
- structural performance (ASTM E 330)
- thermal cycling (AAMA 501.5)
- testing to 150% of design loading.

Other protocols can include interstory displacement tests, seismic movement, window-wash anchor load testing, and impact simulations. While failures are disappointing during the performance mock-up, it allows the team to identify issues and provide solutions prior to fabrication. To put it mildly, an issue is much better found in the mockup than on the 15th story of an operational tower.

Like the early-phase analytical tools, performance mockups represent just one of a host of advanced methods building teams can use to optimize building performance. As the case studies and design principles outlined here show, all can assist clients in achieving long-term operational goals by designing high-performance facades that control solar gain, glare, acoustics and air infiltration. Through a combination of metal screens, fritted glazing, aluminum shades, and vertical or horizontal GFRC fins, the projects can make the "material mix" a palette of solutions for performance needs. But the use of multiple façade materials—while often the key to a successful design concept—also can bring a host of issues, such as ensuring continuous insulation (CI), controlling heat gain and moisture ingress, and even impacting warrantees for individual components.

The solution? Maybe it's best described as holistic collaboration and integrated, multidisciplinary project development. Whatever its name, the process certainly calls for early and frequent communication between the architect, engineer, client, general contractor and façade fabricator.+