Photo: Ed Wonsek; courtesy of The Architectural Team

The Raffles Back Bay Hotel and Residences in Boston use a unitized curtain-wall system with an estimated lifespan of 60 to 70 years.

Longevity and Sustainability of Curtain Walls

Will your facade last a few decades or a millennium?

Sponsored by The Ornamental Metal Institute of New York

By William B. Millard, PhD

Designing a building with sustainability, resilience, and longevity in mind calls for a recognition of complexity and interdependence. Each component of a building contributes to its embodied and operational carbon footprint, its occupants' experience, its architectural expression, and its economic performance. The building envelope is a particularly powerful determinant of these outcomes, since it comprises a large volume of materials, endures climatic and atmospheric stressors, and mediates between exterior and interior environments, transmitting or consuming widely varying amounts of energy in the process. The contemporary curtain wall, a product of over a century of technical evolution, can be one of a building's vulnerable points, showing its age faster than the rest of the structure does. The converse of that observation is that improving a curtain wall's quality and longevity is an opportunity to realize powerful gains in the whole building's performance.

The 2024 Design Challenge sponsored by *Metals in Construction* magazine and the Ornamental Metal Institute of New York, eliciting proposals to design the curtain wall system of a new building at least 50 stories tall for a site on Broadway in midtown Manhattan, posits at least a 75-year anticipated service life for the proposed systems. This represents a substantial extension of the longevity commonly observed and expected in contemporary practice, say several experts in sustainable envelopes.

Mic Patterson, ambassador of innovation and collaboration at the Facade Tectonics Institute (FTI) and a member of the Design Challenge jury, cites a remark by Anthony Wood, executive director of the Council for Tall Buildings and Urban Habitat, at an FTI conference. "He said, 'How long should a building last? It should last until we're done

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Learning Objectives
After reading this article, you should be able to:

1. Apply your understanding of new efficiency properties for facade design with the goal of increasing curtain-wall longevity and reducing embodied carbon.
2. Learn serviceability characteristics that can contribute to the life cycle of a curtain wall.
3. Analyze the recyclability potential of constituent parts of a curtain wall.
4. Balance resilience and sustainability attributes with properties promoting healthy interior environments for occupants to achieve the best performance and aesthetic goals.

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with it,' which I think is the right answer.... They should be modifiable, adaptable, and repairable as need be until we are completely done with them." There is no one-size-fits-all criterion for a facade system's durability, Patterson says. "It needs to be adaptable enough to accommodate changes in use and all of the forces of obsolescence."

Patterson commonly encounters facade contractors' expectations of 20 to 35 years for the life of a curtain-wall system, with 50 years as the customary upper limit, and he finds these figures unnecessarily low. "That ignores the synchronicity that needs to exist between the aspirations for the building itself and the facade system," he continues. "If you've got a building that is designed to last 100 years and a facade system that's still designed to last 75 years, you end up needing a new facade system before the building expires. And if you put a new one on there, that's good for another 75 years, then you lose 50 years of facade-system service life. And so there's all kinds of wasted durability going on in buildings and facade systems just because we don't pay attention to that." There is no reason, he believes, that certain buildings reflecting the most advanced realistic design and construction practices—coordinating components' durability rather than leaving it to chance—cannot last a century, perhaps even 1,000 years.

In the U.S. curtain-wall industry, Patterson reports, it is common to market systems with a 35-year expectancy as "zero-maintenance systems to the building owners, which is what they want to hear. Basically, what we're saying is, 'This thing is good for 35 years, and then it's done,' because there's no way to maintain it or retrofit it." With few options for replacing or upgrading a facade system, "the only viable economic strategy in too many cases is to just rip the entire thing off and put a new one up"—the antithesis of sustainable practices, particularly when designs unwittingly create obstacles to the disassemblability, reuse, and recycling of materials.

The concept of zero maintenance, though attractive from a short-term perspective, appears roughly as realistic as a perpetual-motion machine. Patterson and other commentators contend that more farsighted approaches are within reach, however, for professionals who take a long-range view of the material cycles involved in design and product choices.

SYSTEMIC AND COMPONENT LONGEVITY

"Facade-related design decisions often come with tradeoffs," comments Isabelle Hens, environmental designer at the San Francisco office of environmental design consultant Atelier 10. "The window-to-wall ratio will impact embodied carbon, since the glazing assembly will have a different embodied carbon than the opaque assembly; operational carbon and thermal comfort, since it will alter the solar heat gains; interior occupant experience, since the window-to-wall ratio determines how much daylight and direct sun enters the space; and exterior architectural expression, by changing the facade articulation." Decisions about each of these factors are best taken holistically, she adds, rather than assessing components in isolation.

The lifespan of a complete system comprises the lifespans of its parts, which frequently differ. Vishwadeep Deo, facade consultant and vice president at Thornton Tomasetti, points out that once a curtain-wall system is installed, its enclosure infrastructure is "derived from multiple different components and pieces. Individually, those component pieces themselves have a very different lifespan; some could go away within 20 [to] 25 years and need to be replaced, while some of the others with metal in the enclosure could last up to 75 and beyond."

Expectations for the durability of aluminum, glass, and other materials depend on multiple variables, Deo notes, including location, exposure to assorted destructive forces (weather, salinity, ultraviolet light, and pollutants), and maintenance cycles. A building in a marine environment will face high risks of corrosion, as will one exposed to acid rain. A system that includes sealants will need periodic inspections and replacements. A curtain wall system's design can add to these variables, he continues; even if an owner performs regular maintenance and preserves the overall integrity of a facade, sections of it may be inaccessible and may fall into neglect.

Curtain-wall technology has progressed considerably over the decades, steadily improving in thermal performance while generating challenges in serviceability and durability. Brian McFarland, AIA, principal at CetraRuddy, traces the evolution of facade technology from early examples like SOM's Lever House, the second curtain-wall building in New York City (after the United Nations Secretariat Building), to today's unitized curtain walls and insulated glass units (IGUs). After "stick-built curtain wall, which was aluminum extrusions that you then applied glass to, and then you put a pressure plate on the outside of the glass," came unitized curtain walls in four- to five-foot units going floor to floor, a less continuous skin than the previous generation's "multi-floor continuous verticals."

Further improvements included thermal breaks with nonconducting isolators at the pressure plate, then structurally glazed curtain walls with "no metal on the outside of the wall, so even though it's not the greatest insulator in the world, you do have the IGU outside of the metal to create some thermal break between the exterior environment and the metal." The unitized curtain wall improves speed of erection and reduces labor costs; it is "one step better than what we used to call thermally broken, but it does also have its issues," McFarland continues, including thermal bridging from aluminum framing behind the glass and condensation from insulation on spandrel panels with a galvanized back pan for protection during shipping.

IGUs came to dominate curtain walls around the 1980s, replacing the early single glazing of the cheap-energy era predating the 1970s petroleum crisis, improving on early curtain walls' poor insulation with a modular assembly: a frame, double (later triple or quadruple) glazing, spacers, hermetic sealants, thermal breaks, and optional components including interior thin-film coatings, fritting, and argon, krypton, or a vacuum to reduce heat conductivity in the cavity between the panes. Interior condensation is the bugbear of IGUs, since seals are the most common site of failure. Gaskets outperform wet seals, McFarland says, and unitized curtain walls require less maintenance than brick cavity walls, which have multiple intersections between components and "wet seals that have to be maintained continuously over the life of the building; [brick walls] may ultimately last longer, they may ultimately stand longer, but they require more recurring maintenance than a well-engineered glass curtain wall does." Leaks lead to fogging, mold, and oxidation of aluminum and metal oxide coatings, compromising aesthetics and reducing service quality, sometimes leading to the replacement of an entire facade rather than changing out a single IGU, which is often challenging because of inaccessibility.

McFarland identifies several other reasons a modern curtain wall might deteriorate. "One is if you have any finished metal on the outside of the wall, and there are three different finishes you usually have. In the States, it's usually a PVDF [polyvinylidene fluoride] coating; outside the States, it's usually a powder coating." The third finish, anodizing, Images courtesy of Priedemann Facade Experts

METALS IN CONSTRUCTION 2024 DESIGN CHALLENGE WINNER: R-IOT CYBER-PHYSICAL MAINTENANCE

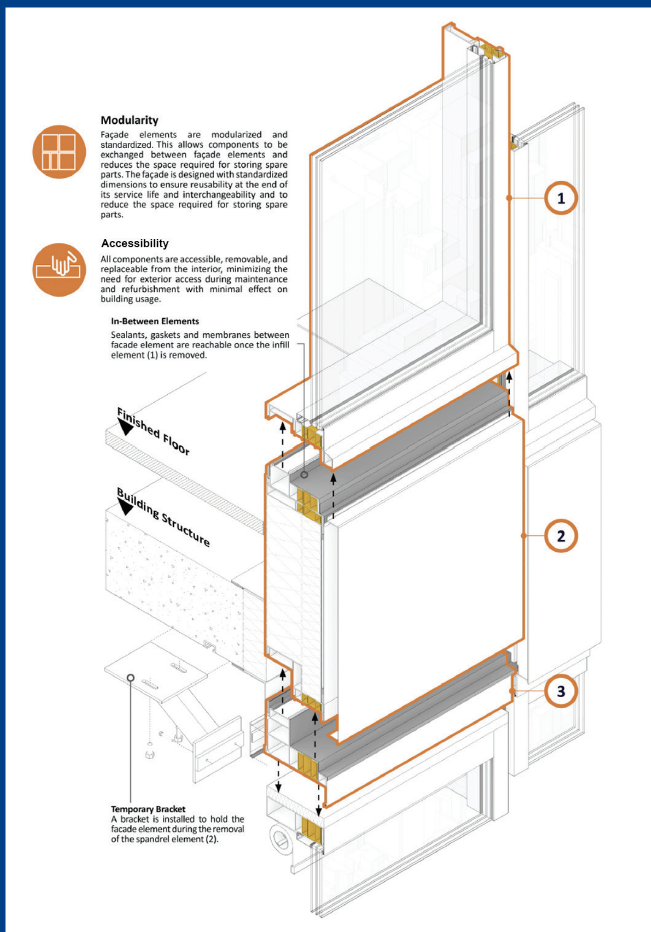

Figure 1. Diagram of major components of the R-IOT system: infill (1), spandrel (2), and terminal (3) elements.

The winning entry in this year's Design Challenge is a facade system rather than a building design. The R-IOT project, revealed after jury deliberations to be the work of the Berlin-based firm Priedemann Facade Experts, combines a dismountable unitized facade system (Fig. 1) with a physical/digital interface that monitors the performance status of components via integrated sensors and a digital representation of the system. (The abbreviation, Priedemann representatives say, combines the Internet Of Things with an intentionally ambiguous initial that could designate Revolutionary, Renovation, Refurbishment, Reduce, Reuse, Recycle, and others.)

During the jury's assessment of competition entries, juror Vishwadeep Deo of Thornton Tomasetti hailed this proposal's innovations: "keeping digital twins and machine learning and AI (artificial intelligence) to run early detection and preventative pattern recognition." The jury unanimously found that R-IOT, although it did not offer a site-specific design for the Broadway address described in the competition's design brief, more than made up for that aspect by proposing a modular concept that can improve the longevity and performance of any curtain-wall system.

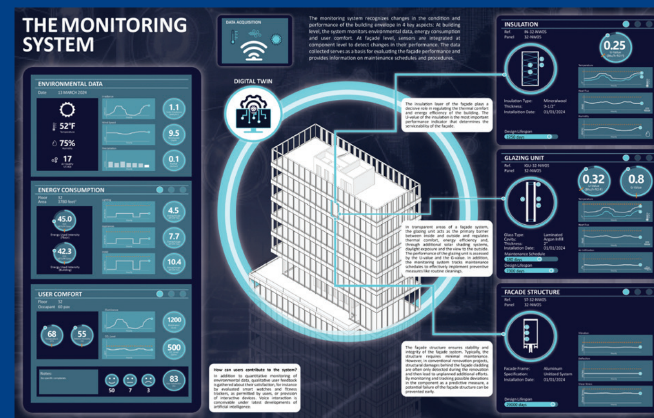

Figure 2. Monitoring system for R-IOT on building and facade levels.

Described in the competition entry as "Revolutionary Cyber-Physical Maintenance and Renovation Strategies to Extend the Lifespan of Facade Constructions," the R-IOT system renders energy-intensive facade refurbishments unnecessary by taking what it calls a "precognitive" approach to continuous monitoring and maintenance (Fig. 2). By continually providing data on three main interdependent parameters—building energy efficiency, occupant comfort, and facade component conditions—the system identifies degradations in performance proactively rather than reactively. When expected and measured performance diverge and components approach a predefined threshold value for failure, the system gives stakeholders a warning that enables timely and appropriate interventions in the form of component removal and replacement or maintenance (Figs. 3, 4).

The infill, spandrel, and terminal elements of the R-IOT facade are all designed for deconstruction, with standardized components in replaceable cassettes accessible from the interior. Transparent, opaque, or partially opaque infill elements can include features such as openable windows, shading systems, and other mechanical elements; sealants, gaskets, and membranes between facade elements are accessible when the infill element is removed. Opaque spandrel elements, the interface between the facade system and the building structure, accommodate a range of cladding elements, potentially including photovoltaics or green wall systems; supporting terminal elements allow staged removal of the system and access to hidden components such as removable polyamide thermal breaks. Chemical bonding is minimized, used only where unavoidable, as in IGUs or laminated glass. A mobile glass-handling machine enables on-site maintenance or retrofitting operations, reducing downtime and carbon emissions from transportation and heavy machinery use.

The system can also accommodate new design elements and material technologies as they appear, allowing aesthetic upgrades in the form of exchanged cladding or insulating components. R-IOT's designers are "pointing to the fact that there is a relationship between these things, and that the service life of an assembly is determined by its weakest link," commented juror Mic Patterson of FTI. "Their approach is that it all needs to be replaceable.... With this kind of strategy, the service life is an irrelevant term, because what you have is

Images courtesy of Priedemann Facade Experts

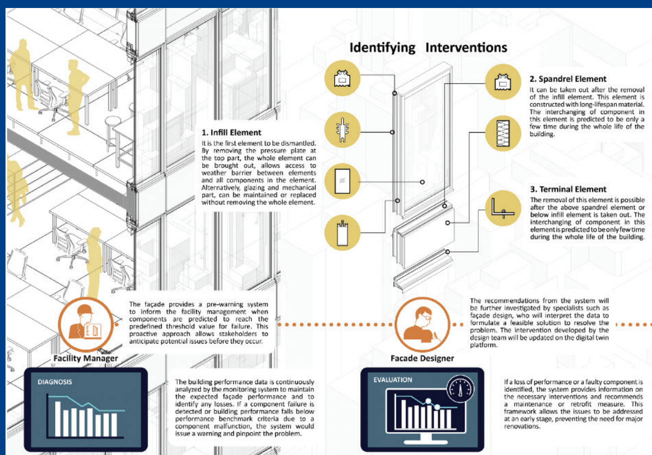

Figure 3. Monitoring system for R-IOT on building and facade levels.

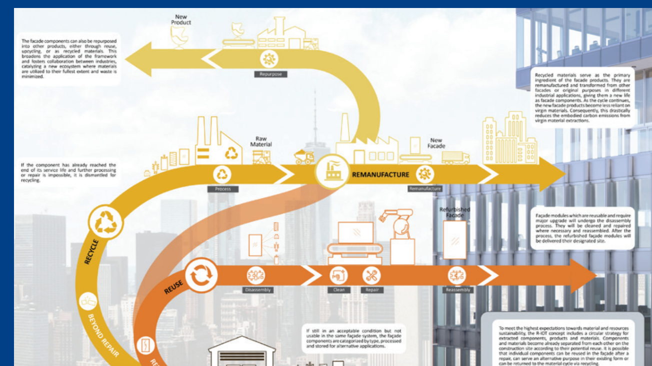

Figure 4. Repair, reuse, recycling, remanufacture, and repurpose of R-IOT components after problem detection and interventions.

a perpetual service life: as long as you can maintain the thing, you can go 1,000 years, and you may not have an original part in the assembly, but it's seen continuous service."

Jurors acknowledge that while the winning entry satisfies the requirements of the brief, a fully realized version of R-IOT will need to address practical questions such as specification of resilient materials and the mechanisms of sensor function. "Looking at U values and the glass performance," observes juror Vivian Fu, an associate principal at Heintges in San Francisco, "the deterioration of the facade, a lot of times, is about air leaks and water leaks. Where's the detection of that?" Stanford Chan of Socotec questions whether the system should incorporate exterior access for maintenance, considering the disruption to occupants that interior access may cause. Use of standardized components, Patterson also notes, can imply potential creative constriction: "The problem with modularity is, how do you give the architects freedom of expression with a modular concept?" That the R-IOT proposal stimulates such discussion, however, commented Jack Robbins, partner and director of urban design at FXCollaborative, is "a good sign that we're getting into little details: how does this actually work?"

used to be more common, but has waned in the U.S. as environmental regulations have increased, though is still more widely available in Europe, he notes. Finishing specialists generally estimate a life expectancy of 20 years for powder coating, 25 for PVDF, and 30 for anodizing. "We will have seen walls that have lasted longer than that," McFarland says, and others that have not.

Recalling "one particularly bad example," a midtown Manhattan building less than 30 years old with its finish visibly peeling off, McFarland cites inexperienced fabricators and installers as sources of preventable problems. The curtain-wall industry has expanded globally in recent years, he notes; many curtain walls "actually get pre-engineered systems from known companies, but there are still the people that are cutting the metal, fabricating it, and putting the glass on." Architects' specifications used to include language requiring use of contractors with experience in the field for a certain period, he says, often five years, but this is no longer the case; lab tests may be the chief form of quality control. With unfamiliar low bidders on a project, along with increasing sizes of IGUs beyond the 5-foot-by-12.5-foot modules that were customary on older commercial buildings, resulting in larger and heavier glass that adds stress to components, unwelcome surprises can occur. "When we get out in the field, we see things that are other than what was on shop drawings or engineering. And that's when you start to worry.... Standardization, by default, should last longer, but it's not the way the world is going. We architects are so spoiled now. There's this temptation to have greater freedom with design, but then you have to be more diligent in your review of the engineering."

Having recently worked on his firm's first two Passivhaus projects, McFarland notes surprising differences in curtain-wall components' contributions to thermal performance. "Triple glazing was really a very incremental improvement," he reports; "other things like the better coatings, frits, photovoltaics (PVs), things that physically impede solar heat gain, are much more valuable than whether it be the argon in the cavity or the third piece of glass. You do get an incremental improvement on center-of-glass U value with triple glazing or argon, but if you have a frit or a PV, then you are actually impeding light energy from entering the building."

The transition from double to triple glazing in IGUs, Deo notes, may also have downsides that offset triple glazing's additional contribution to U value. "The moment we increase the number of interfaces, we are increasing the potential of failure at those interfaces, because in a curtain-wall system, failures happen where there is an interface between two different materials. So from a longevity standpoint, I think we are not increasing or decreasing the lifespan of the insulated glazing to go from double to triple, but we are increasing a little bit of risk."

"In the almost 40 years I've been doing this, there has been a continuous evolution of curtain-wall technology," McFarland says, crediting the sustainability movement that arose in the 1990s and now informs many cities' building codes with driving steady improvements in components. "There are certain things they haven't conquered yet, like completely isolating the aluminum framing, but I do think that things like warm-edge spacers and insulated panels on the inside of opaque panels will dramatically improve that." A curtain wall by definition is lighter than a masonry wall; "it doesn't overcome curtain walls' sins, but there is a tradeoff in the reduced embodied carbon that goes into some other parts of the building: the primary building structure can be lighter."

McFarland maintains optimism about progress in facade systems, contending that "actually, higher-performing curtain walls have a longer effective lifespan" provided IGUs are sized appropriately to avoid excess stress on seals and wall structures are isolated to reduce risks of localized condensation in fasteners for thermal breaks. Still, gradual component degradation strikes him as unavoidable. "There are curtain walls out there today that could last 75 years, there's no doubt in my mind. But at 75 years, setting aside replacing IGUs, I can virtually guarantee you that the finish on the metal is going to be worn; I can virtually guarantee you that the gaskets and seals and sweeps are going to not be performing as well." The fallibility of components implies not only that a maintenance-free curtain wall is a phantasm, but that a wise strategy to prolong a system's life is to design it in ways that make it easier to replace its parts.

That modular approach, on the other hand, runs counter to a trend McFarland and others observe in today's facade systems: "More and more, our curtain walls are bespoke from project to project. In some cases, they start from a basis of engineering. There are two German companies, Schüco and Wicona, who essentially sell their pre-engineered systems to fabricators in Italy or Germany or wherever. But on a lot of our projects we wind up slightly tweaking the details. So, in terms of service life, it goes back to being really diligent about what you're asking for and the engineering that goes into it, because at the end of the day, most buildings are one-off. There, you can't simply rely on a presumed warranty; the upfront understanding of what you're asking for that may vary from the norm is something to pay attention to." Product improvements, particularly in glazing, encourage architects to prefer original designs over standardization. "The genie's out of the lamp now, and it's going to be hard for us to humble ourselves and go back to saying that every curtain-wall grid is five feet. Because the capabilities just keep getting better and better. We can get the crispest, sharpest, flattest glass, and it's much bigger than the glass ever was before. So the capabilities just keep encouraging us to stretch ourselves more."

PLANNING FOR THE ADAPTIVE-REUSE OPTION

An increasingly prominent strategy in some locations is adaptive reuse, particularly commercial to residential, as needs for urban housing outweigh post-pandemic demand for office space. For adapting an existing building's facade or long-range planning of a new one, such reprogrammings can be either a complication or an opportunity. "If the usage of the building does not change hands substantially," Deo notes, "there's a higher chance of reusing what you already have. But in my experience, I think there are more and more projects that are that forward-looking to at least understand, not from just from a capital-cost-investment standpoint but also from an embodied-carbon standpoint, how much of the existing building can be reused."

Adaptive reuse implies that life-cycle assessments of energy and carbon metrics, applied to either the facade or the entire building, should be expanded to consider at least four phases: construction, operation (including maintenance), renovation/retrofitting/recladding (repeatable in some cases, depending on program changes and owners' expectations), and end-of-life demolition or deconstruction (ideally including component reuse, at least in a down-cycling mode, since recycled architectural aluminum and glass usually go to less stressful uses because of purity questions).

"Working with an existing building, from the perspective of sustainability, you definitely are reducing the carbon footprint versus doing full demolition," says Stanford Chan, senior principal at Socotec Group's Vidaris and director of its Existing Buildings Division and Roofing and Waterproofing Division. "Also, if the conversion of that particular building can be done efficiently, then the schedule of reopening is much faster." A facade system planned to anticipate improvements in high-performing technologies will ease transitions between the "Day One" design and a "Day Two" retrofit, Chan says. Reclads or overclads require structural foresight: "You first have to understand whether the existing curtain wall and building can accept the additional load. There are ways to come up with a system to replace the glass in a more efficient manner, as opposed to having to cut out the structural silicone from the scaffold 100 stories up in the air."

Structural analysis, code compliance, and energy-usage studies are the pillars of performance in facade upgrades, Chan finds, though in practice, "the trigger for most building owners is not necessarily the improvement of performance, but to improve the value of the building: to make something old useful again, and also be able to compete with the new Class A office buildings." Commercial-to-residential conversions must handle the transition from fixed glass (prevalent in commercial curtain walls) to operable windows that satisfy residential code requirements for natural light and air, since few mid-century buildings were designed with this scenario in mind.

Owners of Class B or C office buildings, often the prime candidates for conversion as occupancy rates languish in the 40 percent range, sometimes struggle with contemporary energy standards like New York's Local Law 97; new office buildings, Chan suggests, may be planned with the flexibility to accommodate possible future conversion. "If you know you're going to be upgrading the glass," he says, "maybe you entertain an operable window within the opening, which can make it appealing if somebody does want to look at that building as a conversion" later in its life. For existing buildings, matching the programming to the building's footprint is essential for a project to be financially feasible, since pre-conversion floorplans often have dimensions that do not work with existing glazing and may require removal of square footage or creation of new courtyards to meet residential code.

In his experience at Thornton Tomasetti and elsewhere, Deo has seen multiple projects where recladding an older, underperforming building, retaining its structural base, has breathed life, both aesthetically and commercially, into structures that might otherwise have been demolition candidates. As a caveat, he is also aware of a case (without identifying the parties involved) where material defects combined with subpar handling and inspection led to facade failure and eventual litigation. A specialized glass unit "relied heavily on a protected edge panel," he recalls. "I think from a design standpoint, everything was great. It was during the execution, when those products and the panels were shipped, there was potentially some damage done to these edge tapes... and these glass panels happened to be super-sensitive to any moisture ingress." Field personnel unfamiliar with the product failed to inspect the panels when they were mounted onto aluminum frames. The experience, he says, implies that when

Photos: Jason O'Rear; courtesy of El Dorado Architects

POTRERO HILL INNOVATION CENTER, SAN FRANCISCO (300 KANSAS): FACADES TAILORED TO A UNIQUE INDUSTRIAL SPACE

In San Francisco's design district, on a site between two busy thoroughfares (U.S. 101 to the immediate west and Interstate 280 a few blocks east), a developer has placed an optimistic bet on a midrise building relying on a bold, site-sensitive facade to attract the kinds of light-manufacturing tenants that may return the Bay Area to the forward edge of the national economy. Local colleagues of the out-of-town architects have commented that the 150,000-square-foot, six-story Potrero Hill Innovation Center (Fig. 5) "really feels like it's a San Francisco building, which is a great compliment," says David Dowell, AIA, partner at El Dorado, a firm based in Kansas City, Mo., and Portland, Ore.

Figure 5. Potrero Hill Innovation Center viewed from northeast, adjacent to Interstate 80 in San Francisco.

The specific San Franciscan-ness "starts with the bay window," Dowell says; in that city, whose bay-window ordinance allows architects to build out over a property line, "the bay window is the iconic architectural feature, historically, and so the building's playing an instrument in that symphony." The Innovation Center takes its identity from "the composite detailing of the east and west facades," he continues: "the storefront, the curtain wall, and then a system of solid and perforated corrugated metal and openings on either side calibrated to cardinal orientation." The south facade is opaque for thermal control; the north facade is all curtain wall. The east and west facades, "curtain wall with scrim on the outside," take a familiar light-catching industrial form, the sawtooth roof, and flip it 90 degrees to place the "sawtooth bays" in the facades' vertical dimension, the elegantly simple result of El Dorado's strategic thinking about glazing orientation to solar views (Fig. 6).

"What that does is, it creates these light wells that penetrate deeper into multiple floor plates, as opposed to a singular plate of a mid-century factory building in Anywhere, USA," says project architect John Renner. "It allows for a semi-lit, semi-shielding facade, especially on the sides, where it's necessary with the immediate highway next door." The perforated corrugated metal on those east and west sides also aids in compliance with the state's tough CALGreen standards for Sound Transmission Class (STC) levels; building massing is higher on the noisier highway (west) side. "By taking the sawtooth onto the side of the building," Dowell adds, "it opened up the possibility to put a park on the roof; there's a lavishly appointed park for the tenants up on the roof of the building, where the sawtooth would typically go. There were all these opportunities to take a typology from another era and manipulate it based on context and environment."

Figure 6. North and west facades of Potrero Hill Innovation Center, showing sawtooth bay windows on the west.

"This is the first all-electric zero-carbon manufacturing core-and-shell building in San Francisco in at least one if not two generations," Dowell adds. Working with an all-star team including environmental design consultants Atelier Ten, structural engineer KPFF, acousticians Salter and Associates, and contractor Webcor, the El Dorado team navigated San Francisco's often byzantine permitting process (the project began in 2017) with two main points in its favor: LEED Gold-level energy-performance metrics to meet San Francisco's guidelines for envelope design, and a program that fits the highly coveted local zoning category termed Production, Distribution and Repair (PDR). "The city expressed strong feelings that they don't want any of it going away," Renner recalls. "At one point, we even did a study of [possible rezoning for housing], and the city straight-up said, 'No, we can't; we don't want to lose any of our PDR stock.' So having new PDR is a win/win." Considering the other typologies that recent local market forces have over-incentivized, Dowell adds, "the city was really enthusiastic about something that was not high-end residential and was not a tech office."

Atelier Ten's Emilie Hagen comments that "the North facade did the heavy lifting for views and daylight; East and West contributed selectively, while the opacity of the South made it high-performance from an energy standpoint." In allocating performance metrics to the facade and other components, she says, "for embodied carbon, we were working towards project-level goals of keeping total embodied carbon below 500 kg CO_2 equivalent per square meter and reducing 10 percent from a baseline. We had the concrete in the structure do most of the work by optimizing mix designs to reduce cement (and thereby embodied carbon) and going for cleaner rebar, meaning the facade didn't need to be modified in support of

Photo: Jason O'Rear; courtesy of El Dorado Architects

this goal." Renner adds that attention to site orientation and daylight (Fig. 7) "helps limit the need for an over-designed or highly energy-consumptive MEP system."

Dowell notes that the building's design facilitates curtain-wall maintenance. "There was thoughtful attention given to cleaning, which also means if you can clean the facades, you can also get to them and service the sealants. And if there's a problem, you have a system built all the way around the building, including an occupied roof, where you can get to everything but the south-facing wall that abuts the other properties. So the conditions are set for caring for the building appropriately to extend the longevity."

Tenants are not yet in place for the Innovation Center at this writing, though Renner describes the facility as flexible enough to accommodate "3D printing, R&D, heavy CNC machines that need sensitive calibration to do work on these floor slabs, or heavy exhaust systems required for lab work." Developer Spear Street Capital also reportedly has its eye on firms working on robotics or autonomous vehicles as potential tenants—the kind of industries capable of returning vigor to this troubled, beautiful city's employment profile.

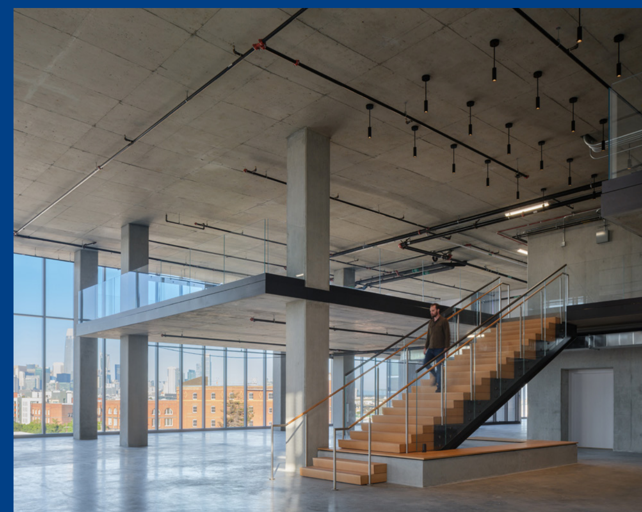

Figure 7. Interior view, Potrero Hill Innovation Center.

any type of new materials are used, risks are lower when contractors have extensive experience with shipping, handling, protection, installation, and maintenance of the component. "A curtain wall fails," Deo summarizes, "when there is an oversight, whether in design or execution or quality control or fabrication."

GLASS AS BOTH PROBLEM AND SOLUTION HEADING

Thinking of the principle that the service life of a building or a component assembly is "only as good as its weakest link," Patterson recalls a startling realization during his research, one that he has passed along to audiences and firms, startling them in turn: that in buildings, unlike bottles, "glass is not recyclable, or at least not recycled. Everyone was a little shocked at that, and it was a dirty little secret of the glass industry, and it's not an easy problem to solve." Circular practices with glass components are more advanced in Europe, he acknowledges, and colleagues have described architectural glass recycling as a process the U.S. glass industry is ready to discuss; glass is durable enough to last centuries, provided it remains unbroken. From an embodied-carbon standpoint, Patterson of the Facade Tectonics Institute says, repeated recycling of glass is both desirable and feasible—"but when we make IGUs out of it, we compromise that service life down to a 20, 25-year time frame, and we make it not recyclable in the process, and then we call it high-performance glazing."

When unprocessed float glass undergoes the secondary processes of coating, laminating, and insulation to become part of an IGU, Patterson and colleagues have argued, its durability is collapsed by "at least an order of magnitude" to 30 or 40 years. The gains in operational energy and carbon are offset by the embodied energy and carbon in the unrecyclable materials. Nickel sulfide and other contaminants in the glass mix can lead to spontaneous breakage in tempered glass and are undesirable for glass manufacturers, who routinely recycle cullet from in-house breakage but are reluctant to accept laminated or insulated materials with coatings and sealants for recycling. (Patterson is aware of a single exception, and not in a curtain-wall building: the Empire State Building's window retrofit in 2009-2010, where "they took the IGUs out, set up a quasi-factory operation on one of the floors, stripped the glass off them, cleaned them rigorously, and made new IGUs out of them.")

As an alternative, his group has proposed a "Millennium IGU" engineered for easy disassembly, either during maintenance or for end-of-life recycling (Patterson et al. 2014). Their Millennium IGU paper cites the Javits Center in New York, whose 1980s-vintage curtain wall was replaced in 2013; renovation was estimated to cost more than replacement, and the old IGUs ended up in a landfill, the fate of many subsequent IGUs as well. Yet "if I can take that thing apart," he says, "I can clean up the inside of it, replace the seal, put it back in place, and it's good to go for however much longer. The notion of the Millennium IGU is that at the end of 1,000 years, there may not be an original component in that assembly, but it's had a continuous service life of 1,000 years."

IGUs designed without maintenance and renovation in mind create a conflict between energy performance and thermal comfort (where these assemblies excel) and durability and recyclability; this conflict compromises the lifecycle carbon footprint of the IGU assembly. Patterson's Millennium IGU concept strives to optimize the lifecycle carbon performance with no compromise to the thermal performance of the assembly. Its methods include using annealed, uncoated, unlaminated float glass and a removable cassette frame; placing low-emissivity film in a removable internal spacer cartridge instead of the surface of the glass lites; replacing wet-applied sealants with dry compression gaskets; using a vented IGU cavity to eliminate pressure differentials, stresses on seals, moisture buildup, and "pillowing" distortions in the exterior glass; and incorporating a removable filter cartridge into the assembly, allowing air passage while excluding moisture and particulates. Removable interior lites allow regular maintenance to be performed from within the building.

Though the Millennium IGU remains an aspirational concept, existing IGU systems continue evolving to improve performance and longevity. Chan and McFarland both cite warm-edge spacers, made of low-thermal-conductivity plastic or composite, as an improvement over stainless steel or aluminum spacers with polyisobutylene seals, which are vulnerable to compromise with condensation of the unit over time. Structural seals between two or three lites of glass, or between glass and the frame, make those components "contingent on the long-term performance of structural silicone," Chan says. "We haven't seen any case studies or evidence where there's been any systemic failure of the structural silicone thus far," though familiarity with its lifespan remains limited.

PROS AND CONS OF AN ALTERNATIVE

Timber is sometimes selected as mullion material in a stick-built curtain wall on account of its renewability, low thermal conductivity, and low embodied carbon. It may not last as long or insulate as well as aluminum, Deo notes, and may "increase the thickness of your walls, and that has additional implications for the project." Its perviousness to vapor migration and tendency to expand, he adds, may make it unsuitable for humid environments, and its combustibility poses "some design limitations that you would need to work with, some fire-engineering consideration that you have to bring in to honor the fire separation between spaces." Architects considering timber in a curtain-wall system, he says, should ask several questions: "What is the space usage on the inside? What is the expected movement that we will see in the timber frames? And how is everything connected back and composed and built?"

In academic research, Hens has found that the use-stage U-value of both timber-based and aluminum-based curtain walls "complies with ASHRAE 90.1 standards for New York and San Francisco... resulting in a negligible difference in energy use and operational emissions" (Hens 2021). When transportation impact is included in comparative calculations of the materials' Global Warming Potential (GWP), however, transport-related GWP in long-distance sourcing scenarios mitigates the advantages of timber in production-stage GWP. The studies emphasize the importance of full life-cycle assessment, noting different advantages for the two materials according to different green metrics (Hens et al. 2022).

EARLY QUESTIONS TO INFORM LATER DECISIONS

Commentators advocate attention to the end of systems' life cycle, beginning at the early stages. "More projects are asking that question," notes Deo: "How can we be more responsible [and] forethink what we can do to facilitate the recyclability of what we are creating? There is more attention being spent in terms of the front end of the project, where we are deciding material composition, ethical sourcing, and sustainable sourcing alternatives.... Lesser attention is being paid to what happens after the life cycle." He imagines "a metric that comes in place that measures that capacity to be recycled; that parameter I do not think exists, but would be worthwhile." He envisions a score system for materials' recyclability, though "that hasn't really evolved to that level in our day-to-day course at this stage."

Some situations are a matter of choice among parallel standards. On a recent project at Princeton University, Deo recalls consulting "the *Design Standard Manual*, which is higher than code requirement for performance. We also tested Passive House, and what we found was that the source of energy for the campus was so cheap that the payback period was way too long to make a rational decision to go Passive House.... So we went in the direction of the design standard that they already had in place."

Codes in Boston, New York, and similar cities, Deo finds, are driving performance and sustainability, in some cases "very compatible with a non-curtain-wall enclosure" with punched windows; with curtain walls, "there are multiple trades that will be operating in the field assembling that wall together, and there is a little bit of a higher risk of failure where the interfaces are going to increase between those two trades. What we need to push for is less prescriptive on the system standpoint, more prescriptive from the performance standpoint."

Aluminum and other metallic components are generally valuable at the scrap stage, Patterson notes, and finishes on metal (unlike those used for glass) burn off in the recycling process, so that a high proportion (though not 100 percent) end up recycled. A persistent obstacle to facade-component recycling, however, is that bespoke components are harder to reuse than standard ones. "This aspect of reuse is certainly exacerbated by the lack of standardization in buildings and facade systems," he says. "If you look at all of the high-profile buildings being built in New York City, what's really driving those is aesthetics.

"There's a lot of exploration of geometric complexity in the facade system, so instead of the old days, where you've got big planar orthogonal surfaces, you've got all these articulations in the building skin, and you end up with a lot of different sizes in the glass or the metal panels and reuse is most often really out of the question. The most you can hope for is that the materials are reclaimed and recycled, and it's not like it's free once it's recycled; there's an energy cost and a carbon-emissions cost in recycling those materials." The logical implication is that design facilitating disassembly will be an increasingly important corollary of design for durability.

CONCLUSION

Addressing the typical tradeoffs among the different priorities a curtain wall serves—occupants' comfort and experience, operational and embodied carbon impacts, architectural expression, and owners' short-term and long-term economic expectations—the environmental design consultants at Atelier Ten offer practical strategies that are best implemented early in the planning and design stages. "First, list all factors, prioritize them if possible, and use different design moves to solve for different performance criteria," says Emilie Hagen, director of Atelier Ten's San Francisco office. "It's possible with thoughtful design to make 'performative exterior shading' (which helps with glare and operational carbon reduction) or other facade moves also part of the architectural expression. Its embodied carbon also has a shorter payback. Similarly, avoiding exterior shading where it doesn't provide performative benefits and only serves an architectural purpose can be rethought to minimize embodied carbon while still making an aesthetic statement."

A second step, Hagen says, is to "set project-level goals, so you can trade off between the facade and other parts of the building." Her third recommendation is to "quantify whichever performance criteria you can through analysis, and lay out key metrics for each in a comparison table to help decision makers. While most performance criteria for facades are not inherently comparable to each other, evaluating each design move by seeing how much it moves the needle for each criterion is helpful for holistic evaluation."

Owners can make more responsible decisions when they recognize that short-term cost cutting is usually a euphemism for shifting costs onto the Earth. Design and specification decisions are more responsible when they account for maintenance and envision the full lifespan of the building, including deconstruction and recycling in a circular cradle-to-cradle process. Patterson's

CONTINUING EDUCATION

Photo: Ed Wonsek; courtesy of The Architectural Team

RAFFLES BOSTON BACK BAY HOTEL AND RESIDENCES: ELEGANCE IN A DIFFICULT SHADOW

The first North American mixed-use building for the Singapore-based Raffles hotel chain relies on its advanced facade to turn the unusual constraints of its location into opportunities to create distinctive living and gathering spaces. The 35-story, 430,000-square-foot tower, hosting 147 guest rooms and 146 residential units, occupies a tight site (about 10,000 square feet, says project manager Alexander Donovan of The Architectural Team, a firm based in Chelsea, Mass.) just 65 feet away from Boston's tallest building, the John Hancock Tower (a.k.a. 200 Clarendon), notorious in the 1970s for shedding glass panes due to thermal and wind stresses and engineering errors. Proximity to the Hancock (Fig. 8) creates a challenge more tangible than a memory of that civic and professional embarrassment: wind loads around the parallelogram-shaped Hancock are substantial, as prevailing winds strike it broadside and then become particularly strong on the Raffles's northern facade.

Another neighboring structure, the 100-foot-tall University Club building, occupies a space on Stuart Street close enough that the Raffles obtained its air rights to cantilever itself some 30 feet over the UClub's property line, establishing enough floorplate area for the units, corridors, and circulation spaces to be financially feasible, notes Donovan. The cantilevers use two sets of large trusses, one located at floors 4 and 5 and one at floors 17 and 18 supporting the upper segment of the building (Figs 9, 10). Though the ground-floor lobby area at Raffles is distinctive,

Figure 8. Raffles Boston viewed from west along Stuart Street, with Hancock Tower in partial view at left.

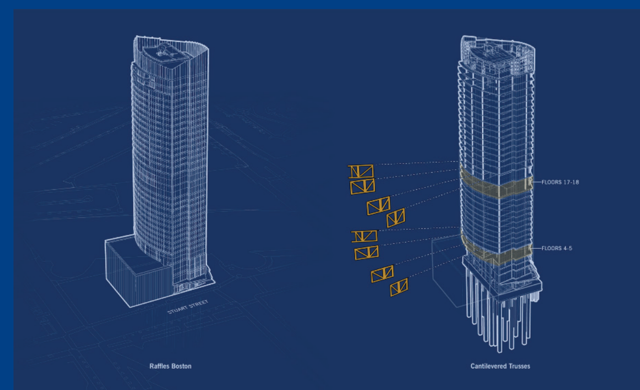

Figure 9. Structural diagram of Raffles Boston shows trusses for cantilevers at floors 4-5 and 17-18.

its three-story sky lobby at the 17th floor, site of the second cantilever, is the signature space. "The real magic," Donovan says, "is, as a hotel guest, when you take the express elevator and get off at level 17, you're open to a view of the Boston skyline that not a lot of hotel lobbies have the opportunity to provide… accented by the floor-to-ceiling glass and a three-story stair atrium [looking] out onto the Charles, a nice view of Back Bay, and almost over to Cambridge."

The Raffles has a unitized curtain-wall system, which Donovan calls "basically a curtain-wall version of a rain screen… you're anticipating taking on a certain amount of water, and the system itself, the extrusions and the configuration of the seals, manages the water to get it outside rather than depending on one full seal." It includes three seals; the outermost seal deflects about 85-90 percent of water between the glass and the beauty caps, and the innermost seal includes weeps and channels to remove condensation and bleed-through (Fig. 11). "We're not based entirely on an exterior seal, which could degrade," he says; the inner seals are not exposed to direct sunlight or the elements and are not prone to ultraviolet breakdown.

"Wind, obviously, was one of our largest constraints on the project," Donovan continues, and the team put a scale model of the airfoil-shaped tower through a battery of wind-tunnel tests, examining wind effects on the overall base building structure, a cladding wind-load study for individual pressures on different areas, and a pedestrian comfort study. "Tests showed that as wind is coming across Stuart Street, which is the strip between us and Hancock, it hits the face of the building and wants to travel straight down to the sidewalk. So one of the requirements the city put on us, which is good practice anyway, [was] a fairly robust canopy over the entry facade of the building to make sure that pedestrians wouldn't be exposed to undue wind conditions." Another study aimed at long-term maintenance was a field reglazing test, where they removed a panel from the mockup, then reglazed it as though it were being executed in the field from the swing stage of the roof-mounted building maintenance unit (BMU), the cranelike system used for window washing and routine services including glass replacement.

Energy modeling indicated that the southern, eastern, and southwestern facades would need the most resistance to solar heat

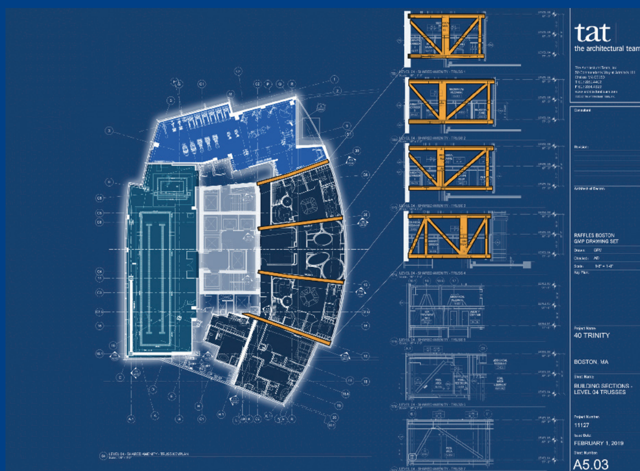

Figure 10. Structural diagram of level 4, Raffles Boston.

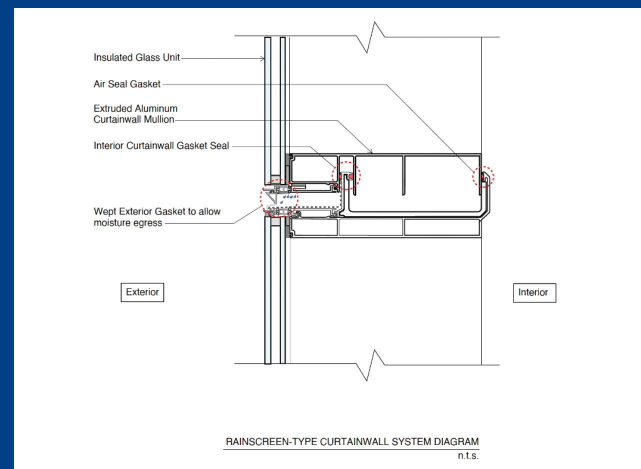

Figure 11. Diagram of Raffles Boston's curtain wall system with rain-screen features.

gain, achieved in part with increased low-E coatings, balanced at different areas to maintain a homogenous appearance. Donovan attributes the tower's wind and energy management, along with certain amenities, in part to its tapered form (with the narrowest dimension facing the Hancock) and in part to how its programming follows its orientation, which he describes in nautical terms. Outdoor spaces used by residents and guests, including a terrace connected with the Long Bar on floor 17, are "biased towards the south of the building, which is really in the lee of the building.... Even though you've got a 28-degree day, because you're in the lee of the building, we've got the curtain wall wrapped around the corner, so there's not a lot of wind in that area, and you get the benefit of the morning sun. That's a really pleasant space, and we've duplicated that on other floors: the level 21 residential amenity space has a similar balcony, it gets the morning sun, and there's no wind."

Donovan acknowledges that replacing curtain-wall panels would be arduous, since replacement would have to occur in the reverse sequence from construction. To replace a unit on a high floor, "you couldn't just pop that one piece out and replace it with another; you'd have to remove everything above it [and] around it to either side. So it's a little bit like building Legos.... When your building's almost entirely glass, you want to get the maximum service life." The team anticipates a lifespan of at least 60 to 70 years for "full service of the entire system"; for components such as gasketing with shorter expectations than the aluminum and glass, he estimates 40 years. A key question in the design stage was balancing aesthetics and serviceability: "How do you service this while the system while it's on the building, because obviously, it's not financially feasible to remove large components of the curtain wall, service them, and then put them back on the building.... In a perfect world, if you want the most easily serviced building, you'd have almost no windows." In an 85 percent glass building, the combination of the unitized curtain wall, a robust BMU, thorough testing, and rigorous construction-stage quality control aims to keep the Raffles in shipshape.

observation of "wasted durability" in many current facade systems implies that design and construction teams might bear a converse concept in mind: "coordinated durability," a condition where the longevity of components is known or monitored, maintenance responds to local signs of degradation before they lead to more general failures, and a building envelope's service life matches that intended for the building as a whole.

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