Ultra High Performance Concrete Panels for Prefabricated Wall Assemblies

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ABSTRACT

Architectural Ultra-High Performance Concrete in thin cladding panels has been established as highly suitable material for high performance back ventilated and drained cavity wall facades. This paper investigates the current applications of A|UHPC in unitized/panelized wall systems and the potential uses and innovations possible with A|UHPC mechanical properties, characteristics, and manufacturing methods.

Ultra High Performance Concrete (UHPC) offers new capabilities for structural and aesthetic architectural applications. UHPC is an order of magnitude stronger and more ductile than high strength precast concrete, and it performs exceptionally well in demanding environmental conditions. Its strength derives from the carefully calibrated ratio of engineered ingredients and a mixing sequence that packs molecules together closely to create very tight bonds.

The high packing density yields excellent flexural and compressive strength, while virtually eliminating the capillary pores that cause freeze-thaw degradation in other cement-based products. Its distinct material properties provide opportunities for greater spans, thinner profiles, more complex geometries, and higher performance in extreme climates than glass fiber reinforced concretes (GFRC), terracotta, or metal reinforced pre-cast concrete products, while maintaining competitive installation costs.

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INTRODUCTION

In today's rapidly changing construction industry, facade designers, manufacturers, contractors, and installers face the necessity to advance their methods, improve techniques, and generally stay competitive under ever-tightening strictures of time and budget, codes and client demands.

In this context, off-site construction or prefabrication of building components and systems stands out for the capacity to adapt to changing design methods, leverage numerous associated technologies, speed delivery processes, and respond to complex project requirements. Prefabrication is not novel in itself. The idea of completing building components off site and then placing them into construction in an already-assembled state took on particular relevance with the mass production of the Industrial Revolution. The nineteenth and twentieth centuries have had many textbook examples of the practice.

Currently, though, shipbuilding and aeronautics use prefabrication more extensively and adventurously than architecture (Montali, et. al., 2018). While many do engage in the practice for buildings, prefabrication still has enormous room for growth, especially because it offers many advantages across the design and construction process.

Wall design figures prominently in discussions of prefabrication. Building enclosure is the focus of expanding component complexity and rapidly updating energy codes, as well as notably altered methods of design and delivery. Add to those issues clients whose expertise and concurrent expectations are ever-increasing, and the stakes for building enclosure cost and performance are higher than ever.

Prefabricated wall systems can take advantage of the material properties of Architectural Ultra High Performance (A|UHPC®) panels and vice-versa. Research into high strength category of concrete dates to the 1970's, with additional relevant advances in the 1990's. It implements advanced material science to elevate the ingredients of concrete to considerable improvement in structural and environmental performance over conventional varieties of the material. Various types of pre-fabricated wall assemblies have gained prominence and are continually innovating alongside new cladding materials. The advantages of A|UHPC® panels allow for economies and improvements across a number of connecting and adjacent components in prefabricated systems through a selection of typological variations.

FACTORS CONTRIBUTING TO PREFABRICATION OF BUILDING ENCLOSURE SYSTEMS

Unitized wall fabrication has been an option for high-rise commercial construction for more almost 80 years now. In that time, its use, including unitized glass curtain wall, has dramatically increased. Once limited to high-rise construction only, only unitized wall fabrication has found its way into mid-rise construction and a broader range of building use types, ranging from cultural institutions and health-care facilities to mixed-use commercial and residential structures that would have previously been built entirely on-site.

Recent Trends

Demands upon building enclosure systems have intensified within the last 15 years with greater emphasis on light weight and layering in facade systems to achieve both aesthetic and performance design intent. The design challenge is to meet the high-performance building enclosure targets, to maintain control of weight and expense (related to the primary, secondary and tertiary structure cost), and to have a durable edifice that defines urban space and delineates the form of the building in a meaningful way with singular architectural character. All this must be achieved within 7 to 10 inches of wall depth. The focus that many contemporary designers have on surface–pattern and variety, color and value contrast, texture and materiality in thin material profiles–derives from the economic pressures on high-performance building enclosures.

Market Forces

While the unitized curtain wall sector is expected to grow, construction generally has had stagnant productiviy. Financial analysts for the construction industry are forecasting steady positive growth in the exterior wall systems sector. A marketsandmarkets.com study from December 2017

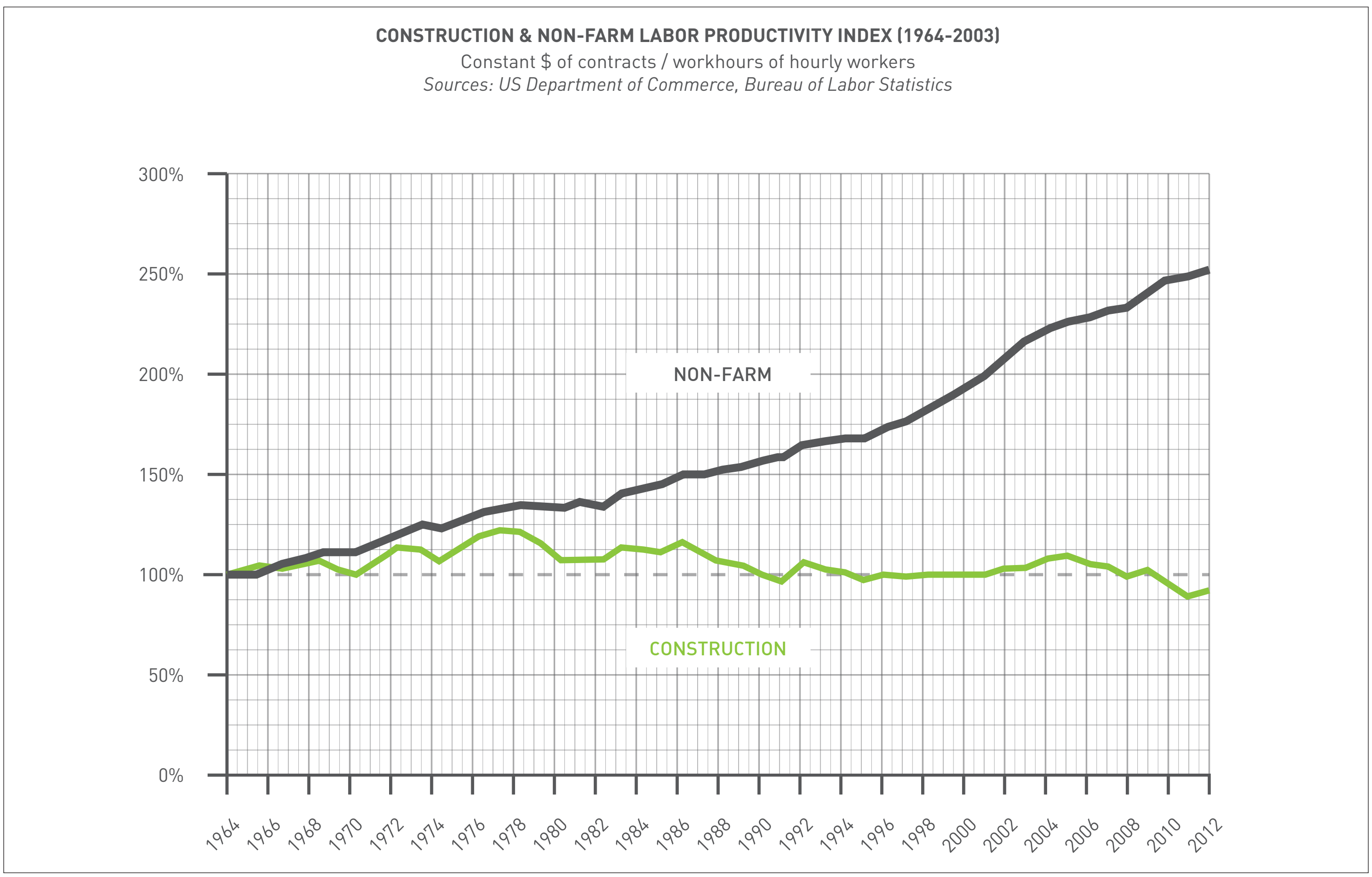

FIGURE 1 *Source: Paul Teicholz, Labor-Productivity Declines in the Construction Industry: Causes and Remedies, AECBytes, March 14,2013*

predicted the exterior wall systems market size will grow from USD 186.02 Billion in 2017 to USD 278.82 Billion by 2022, at a CAGR (compound annual growth rate) of 8.43%, stating, "the Curtain wall segment [will have] the highest CAGR during the forecast period" (Global Forecast to 2022, 2017). Such market expansion leads logically to the recent consolidation of large scale manufacturers and unitized wall systems companies (Gartner/Permisteelisa, Enclos collection of companies, Apogee/EFCO, Kawneer/ ALCOA) as well as the creation of all manner of new 'façade specialty' companies, consulting firms, and design service offerings from manufacturers and builders related to facade installation and facade pre-fabrication.

Meanwhile, the construction labor market has lagged behind the growth of recent years. "For the nearly half-century through 2012, annual labor productivity growth in the US construction sector averaged close to zero, and it has been negative for the past two decades" (Garcia, 2014).

Additionally, the United States lost 1.5 million people in the construction sector due to the 2008 recession. These workers have either retired or found work in other industries, leading to critical labor shortages in the resurgent economy. Along with a decades-long productivity challenge, a new approach to design, construction, and project delivery is essential to the economic future of building in the country. Off-site construction and prefabricated building systems that are able to leverage new design and fabrication technologies are thus essential to address the productivity stagnation and labor shortage.

BENEFITS OF UNITIZATION

Quality and Precision

Because the assembly of multiple critical components is transferred to the factory environment, where parts are milled from CNC equipment and fabricated on jigs, compared to the looser standards and practices of the construction site, quality and precision are improved notably. Prefabricated wall units are easy to test for structural and water/air infiltration and are often common practice, allowing for results to guide assmbly protocols and QC/QA systems. Steel elements can be more easily welded rather than simply mechanically fastened. Tighter tolerances are possible as a result. Likewise, QMS procedures are more easily established, managed, and implemented with good training, efficient workflows, and clear protocols. Although site commissioning cannot be completely eliminated, assemblies can be checked before delivery to the site, reducing the cost and complexity of on-site inspection and commissioning.

Environmental Concerns

The quality and precision of factory-built wall units allow the execution of engineering efficiencies and coordination of components that compare faborably with conventional walls that are field-set and installed by separate contractors. Prefabricated wall units accordingly can achieve high r-values, low air/water infiltration incidence and notable energy savings in thin wall sections. The efficient waste reduction and recycling management of the factory site compared to the construction site result in additional environmental benefits.

Schedule and Budget

Unitized wall systems save time and money combined across a number of issues. (Zuniga, 2017) Components that are customized for the specific design, performance, and aesthetic criteria of a given project allow for better prediction of costs and more effective engagement of value engineering, with fewer change orders and unforeseen conditions, especially under those types of project delivery which emphasize early pre-construction collaboration. The symbiotic relationship between off-site and on-site processes becomes critical to project delivery.

Dry time (for unitized installation) is up to 85% faster than on-site glazing, expediting the time it takes to close the building. Other projects have claimed a 90%-10% relation of off-site to on-site wall construction (Zuniga, 2017).

Because prefabricated systems can typically be constructed concurrently with the building structure, pre-fabrication allows for significant schedule compression. Enclosure for the lower floors can be attached while the structure for the upper floors is ongoing. The sequence of work is better organized and more efficient on site when unitized/prefabricated sectional components are involved. Frequently, such procedures require less labor, while also allowing work to be moved from expensive labor markets to more affordable ones–such as component assembly in a high-bay space in Lebanon, PA for a project in Manhattan/NY.

Safety

Assembly of building components indoors in a factory away from the construction site reduces the occurrence of accidents relating to a number of factors. The circumstance of workers having mishaps related to working at height is no longer a danger. Also, exigencies of work by unrelated trades or companies are reduced or eliminated.

The weather—the construction industries nemesis—is taken out of the equation. Materials and labor are not affected by the change in moisture, temperature or wind. Materials that rely on temperature and moisture conditions to properly adhere and cure are better proected. Factory assembly of building sections reduces risks for contractors and building project owners—addressing one of the higher priorities for owners—increasing certainty in the building process.

UHPC DEVELOPMENT AND USE

Ultra High Performance Concrete (UHPC) is a category of concrete characterized by high strength, low water absorption, and high resistance to waterborne and airborne chemical degradation. Although extremely high compressive strengths can be achieved with UHPC, for thin architectural elements, the mix design and panel design favor flexural strength over compressive strength.

The basic raw materials of UHPC are familiar to everyone who knows concrete: water, sand, cement, silica fume, and plasticizers. However, UHPC is an order of magnitude different from traditional categories of concrete. No special resins, cellulose, or polymers are used to achieve the outstanding properties of architectural UHPC. Rather, the distinctions lie in the size, geometry, and carefully selected chemistry of extremely small particles that combine under exacting mixing, vibration, and curing regimens to form a base matrix. The design and calibration of UHPC formulas involve state of the art concrete chemistry and micro/nano-particle engineering to optimize chemical and mechanical bonds.

Developed initially for large and specialized civil engineering applications that could benefit from its high strength and durability under extreme conditions, UHPC has been in use in Europe for more than 30 years. Such applications—seawall anchors, bridge abutments, super thin arches, bridge decks, and pre-cast beams for nuclear power—are still the predominant use cases for UHPC.

The first structure in North America, the Sherbrooke Pedestrian Bridge, was built in Quebec, Canada in 1997. The first pre-cast UHPC application in the United States was for waffle-slab deck panels for a short span bridge (Little Cedar Creek) in Iowa in 2006. In 2014 a large project for a 2 km viaduct near Geneva in Switzerland was refurbished with 1.5in (38mm) overlay of UHPC for a triple purpose: strengthening the road deck, waterproofing the structural concrete and providing new wear surface for the roadway, which underscored its combination of mechanical and durability advantages. Today in the United Sates, the use of UHPC by volume, is dominated by bridge deck joint grouting.

However, today a wide variety of formulations are being developed that advance the performance characteristics of this category of concrete and adhere to the requirements of specific applications, everything from cast refractory components and injection-molded complex parts to extruded profiles. Industrial, architectural, and landscape design professionals are now embracing UHPC for its aesthetic potential in addition to its outstanding strength and durability. All the properties and characteristics of UHPC that are beneficial in special civil engineering construction applications are harnessed when UHPC is molded into high quality architectural elements, including surfaces, shapes, and assembled systems that were not possible until recent years.

Manufacturing

Production of A|UHPC is more akin to the flow of automated manufacture than to pre-cast concrete operations. The process optimizes systems, equipment, and digital control of mixing and casting. Cured panels are then processed in ways similar to high volume panel or stone processing

FIGURE 2 *Chillon Viaduct, Geneva Switzerland, road surface topping with UHPC*

FIGURE 3 *(Left) Little Cedar Creek Bridge, Iowa DOT, 2006. (Right) Bridge deck Grouting with UHPC*

operations. Flat sheet or 3D shapes are typically trimmed to size with CNC equipment. For comparison, an efficient pre-cast or spray-in GFRC operation may produce several hundred square feet of material each day. An A|UHPC composite manufacturer may produce several thousand square feet a day. Each operation of course has similar cure time. Ultra High Performance does not yet mean ultra fast cure to concrete design strength. For now, 28 days is the standard. Accelerated cure for UHPC may soon be possible. It is easy to achieve in lab scale tests, and it has promise relative to high volume production.

Sustainability

These properties also lead to notable environmental benefits. Raw materials are sourced regionally for a product that is manufactured in the United States. A good strength-to-weight ratio results in reductions to necessary installation labor and associated transportation costs. Recycled content using by-products from other industrial and energy industries has been proven viable, but as yet this has not been introduced into a high volume manufacturing process. A\UHPC does not contain any hazardous (carcinogenic) materials. Embodied energy compares favorably to steel, aluminum, and glass or even dimensioned stone. With material durability and resilience per inch thickness as an additional factor, life cycle analysis costs are reduced across the board.

Architectural Applications

The Architectural UHPC industry is just getting started in the United States and, in fact, there are only a few fully integrated manufacturers of Architectural UHPC in the world. It will be a very long time before we exhaust potential for the material and its architectural applications. Within the last six years, Architectural UHPC has been installed on government buildings, including foreign consulates, courthouses, university buildings, museums, airports, and commercial office buildings, as

TABLE 1. COMMON CLADDING MATERIALS ENVIRONMENTAL FACTORS					
Cladding Material	Energy per Mass		Thermal Conductivity		Water Tight
	btu/lb	Mj/kg	btu in/(hr ft² F)	W/(Km²)	
Face Brick (4" nom)	1.08 - 1.94	2.5 – 4.5	.44	.077	No
A|UHPC (5/8")	2.07 - 2.32	4.8 – 5.4	.08	.014	Yes
Limestone (2")	2.62 - 3.10	6.1 – 7.2	.12	.021	No
Granite (11/2")	2.54 - 5.98	5.9 – 13.9	.08	.014	Yes
IGU (heat strengthened)	5.10 - 5.80	12.0 – 13.5	2.28	.401	Yes
ACM (3/8")	43.0 - 50	99.5 - 115.7	.16	.028	Yes

TABLE 1 *LCA for materials Source – Life Cycle Assesment of Cladding Products, University of Tennessee, Center for Clean Products 2009 & Carnegie Mellon University, assessment of Taktl panel products 2012, R-Values source ASHRAE Handbook of Fundamentals, and COMNET Manual.*

well as hotel and residential high-rise developments. Applications for Architectural UHPC are varied and include:

1. Cast corners matching the thickness of panels.
2. Shading devices or light reflectors.
3. Screens and lattices (hung or self-supporting).
4. Acoustical barrier and/or diffusion/reflection parts
5. Fins, copings, sills, headers, and water tables for masonry facades.
6. Manufactured permanent form-work for high quality finish face of structural elements .
7. Planters, benches, bollards, and other landscape elements.
8. Columns, beams, and floor spanning slabs
9. Cladding panels (close cladding and ventilated facades)
10. Unitized curtain wall (integrated with glazing assembly or opaque units).

Properties

The material is very strong and durable due simply to its material chemistry, but when combined with today's advanced manufacturing technology and tooling techniques, it can meet an additional order of demands of high performance building requirements, design aspirations, and construction economics. The material is consistent and reliable across a number of qualities that make it an outstanding fit for architectural applications. The qualities that are most advantageous for pre-fabricated enclosure systems include:

1. Mechanical properties are predictable with a very low coefficient of variation.
2. Precisely replicates mold surfaces and geometries, creating limitless possibilities for patterns, textures, and shapes
3. Natural, mineral-based raw materials afford graceful weathering and aging of material
4. Extremely durable and low maintenance, outperforming CIP and many types of stone
5. Inherent strength that allows thinner and lighter panels and profiles than stone, conventional pre-cast concrete, and most profiled terracotta
6. Higher span to weight ratios that result in fewer attachment points and sub-frame components, reduced installation labor, and lower specialized hardware costs
7. The ability to precisely process and finish parts post-casting—CNC cutting, drilling, media-blasting—and assemble parts with high performance adhesives.
8. Water tight and minimal water absorption

A|UHPC Facade Panels

Among the numerous possible uses of A|UHPC, cladding panels and unitized curtain wall systems are two notably promising areas of implementation and exploration.

Although architectural UHPC is more expensive than conventional pre-cast concrete or even high performing concrete pound for pound, the crucial difference is that far less material is used to achieve the same panels sizes or shapes. When properly comparing the cost of full wall assemblies and installation labor, architectural UHPC is likely to be less expensive and higher performing than pre-cast or traditional GFRC. In transportation, a truck can freight four times as much surface area of A|UHPC as

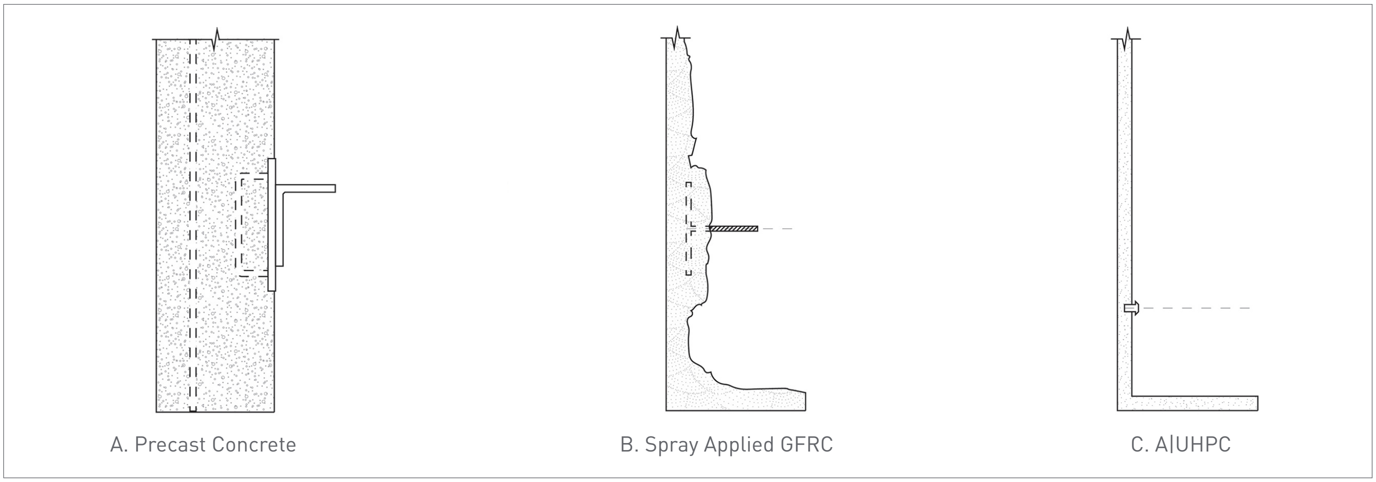

FIGURE 4 *Comparison of concrete/cement based facade material thickness.*

architectural precast. Then, the A|UHPC can be offloaded with a forklift, rather than a 15-ton crane.

Panel Sizes and Thickness

While the particles in UHPC are much smaller and packed more tightly than conventional concrete, the density of A|UHPC is actually similar, averaging 140 pounds per cubic foot due to the inclusion of AR Glass fiber reinforcement.

Panels of 5/8" thickness weigh 6.90 pounds per square foot, allowing easy manufacture of different panel sizes. This weight and area is only 25-35% of the weight of 1½"–2" thick stone and 10%-15% of the weight of 4"-6" precast concrete. Further, stone would likely be divided into smaller panels for the same area coverage. The weight of 5/8" architectural UHPC compares most closely with that of Insulated Glass Units. The possibility to manufacture thin panel sizes up to 60" X 144" makes architectural UHPC cladding panels attractive for both ventilated facade and unitized curtain wall applications.

For the same area of facade, the difference in weight dramatically changes not only the wall assembly options and the type of structure required to hang such panels/parts, it also trades thickness and weight for insulation and rentable floor area. For multi-story and high-rise buildings with large areas of opaque facade surface, the differences can be on the order of magnitude of millions of pounds of weight and either an increase in wall insulation or thousands of square feet moved into the rentable area side of the ledger. The reduced weight of the facade can reduce the size of the foundation and the size of primary structural framing at the perimeter of the building. In addition, thinner, lighter panels/parts give installing contractors a multitude of choices of the means and methods employed on-site to take best advantage of their resources and skill sets. For cladding, this means the ability to hand-set from scaffolding and booms or mast climbers versus the necessity of cranes for pre-cast and spray-in GFRC.

Thin architectural UHPC panels have higher flexural strength than most cement-based composite panels. This is great for the impact resistance and Modulus of Rupture (MoR) needed for thin cladding. The supporting assembly or sub-frame for the cladding system can be similar or equal in cost to the panels themselves. Panel strength has a role in the requirements for attachment. Anchor capacity and flexural strength are the controlling structural performance factors for thin panels under wind and seismic loads. They can affect the distribution and cost of attachment components. Aluminum extrusions and stainless-steel hardware are most commonly specified for attachment systems. Given the costs of these types of non-corrosive metals, the use of architectural UHPC cladding significantly reduces the frequency of anchor points and sub-frame components and thus, the associated cost of material and the installation labor required.

A|UHPC FOR WALL SYSTEMS

Product Flexibility

Blanks producing nominal 4' X 10', 4' X 10, 5' x 10' or 5' X 12' dimensions are most common. Then secondary processing is employed—like dimensional stone—cutting to size and pre-drilling for support connections in the factory. Cast in thin sheets and accurately cut to tight tolerances, panels are produced utilizing process /sheet optimization software or pulling from CAD files.

Panel sizes can range from as small as 6" X 48" to as large as 60" X 144" nominal dimensions (or longer custom sizes).

For structural and serviceability reasons as well as aesthetic intent, there is flexibility in casting thickness and surface texture/pattern profiles. Panels may be attached with concealed undercut anchors, bolted with visible fasteners, or adhered to a support frame. Anchor and fastening capacity is usually the controlling factor. Tension loads from negative wind pressure determine the panel anchor spacing, and this spacing typically results in excess capacity in flexural strength relative to span. A thicker panel leads to greater embed depth for anchors and results in a higher capacity of undercut anchors. With visible fasteners, the capacity is most often determined by the gauge or thickness of the panel rail /fastener connection rather than the panel, since the holes for visible fasteners are oversized and do not engage the concrete.

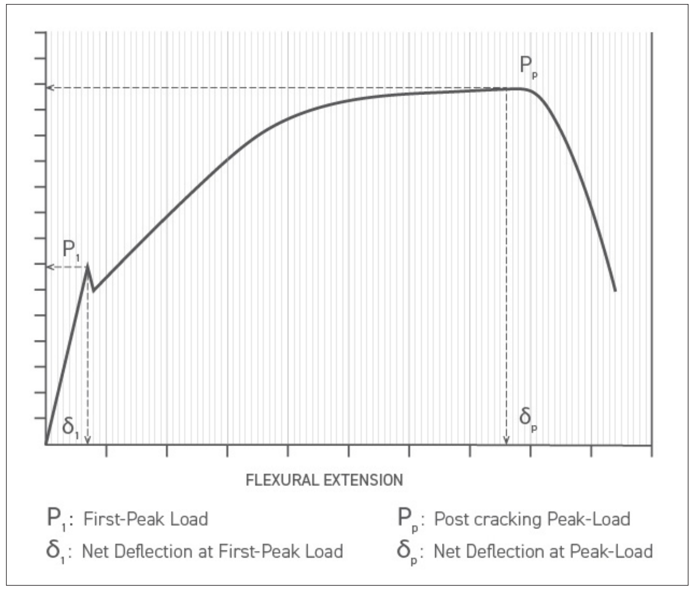

FIGURE 5 *A/UHPC composite behavior - first crack load significantly less than ultimate load*

TABLE 2. COMMON WALL SYSTEM CLADDING MATERIALS

Material	Thickness		Weight		Flexural Strength	
	in	mm	lbs/sf	kg/M2	MPa	psi
Terracotta (typ. 1.5' X 5ft)	1.50	38.10	11.5	56.14	17.20 (min)	2494
Limestone (high density)	2.00	50.80	22.00	107.4	3 - 7	435 - 1015
Granite	1.50	38.10	20.00	97.64	8 - 10	1160 - 1150
Fiber Cement (sheet)	0.50	12.70	5.50	26.85	18 - 22	2610 - 3190
GFRC (spray)	1.50	38.10	8.58	42.96	12-16	1740 - 2320
IGU (2 ply)	1.00	25.40	6.40	31.24	39 (Design) – 80Max*	5656 - 11603
IGU (3 ply)	1.75	44.45	8.92	43.55	39-80*	5656 - 11603
ACM	0.160	4.06	1.56	7.61	15	2175
A|UHPC	0.625	15.87	6.90	33.68	32 - 45 (avg.)	4641 - 6526
A\UHPC	0.750	19.05	8.30	40.52	27 - 35 (avg)	3916 - 5076

TABLE 2 *shows how A/UHPC compares to common cladding materials. Of particular interest is the proximity of values for Insulated glass and A\UHPC in both weight/thickness and flexural strength.*

WALL DESIGN

Straube's Perfect Wall

John Straube's ideal wall delineates the function cavity of the control layers of a Back Ventilated Drained wall. For schematic clarity, he leaves out specifics about material makeup and mechanical attachment to emphasize that basic principles can be realized with some variation in component configuration. The outermost elements are the exterior finish, which has open joints and an airspace behind. The next layer in is thermal control. The membrane and/or sheathing layer controls water, air, and vapor, through any of a variety of permutations in one to three layers. The structure can be the service layer, or additional depth can be added before the interior finish.

Once the province of new and innovative building, Straube's wall is now practically code-required and easily achieved as a typical wall section condition. The relationships between the finish cladding, control layers (continuous thermal insulation, moisture, and air vapor control) and structure are relatively well known, and the materials available that can be employed in these layers are continually being improved. This type of wall construction has greatly benefited from advancements in the performance of AVB/WRB products, continuous insulation materials, and installation methods, allowing for full open joint cladding and/or Pressure Equalized Rainscreen assemblies. Within the last decade many companies have emerged specifically to manufacture and provide related design and engineering services for cladding support systems used within BVDC walls.

The most common implementation of BVDC with A|UHPC is a light gauge steel frame and exterior grade gypsum board sheathing with a membrane and mineral fiber insulation. A|UHPC cladding is supported on a subframe of either aluminum, steel, or stainless steel to support the cladding and hold the cavity dimension

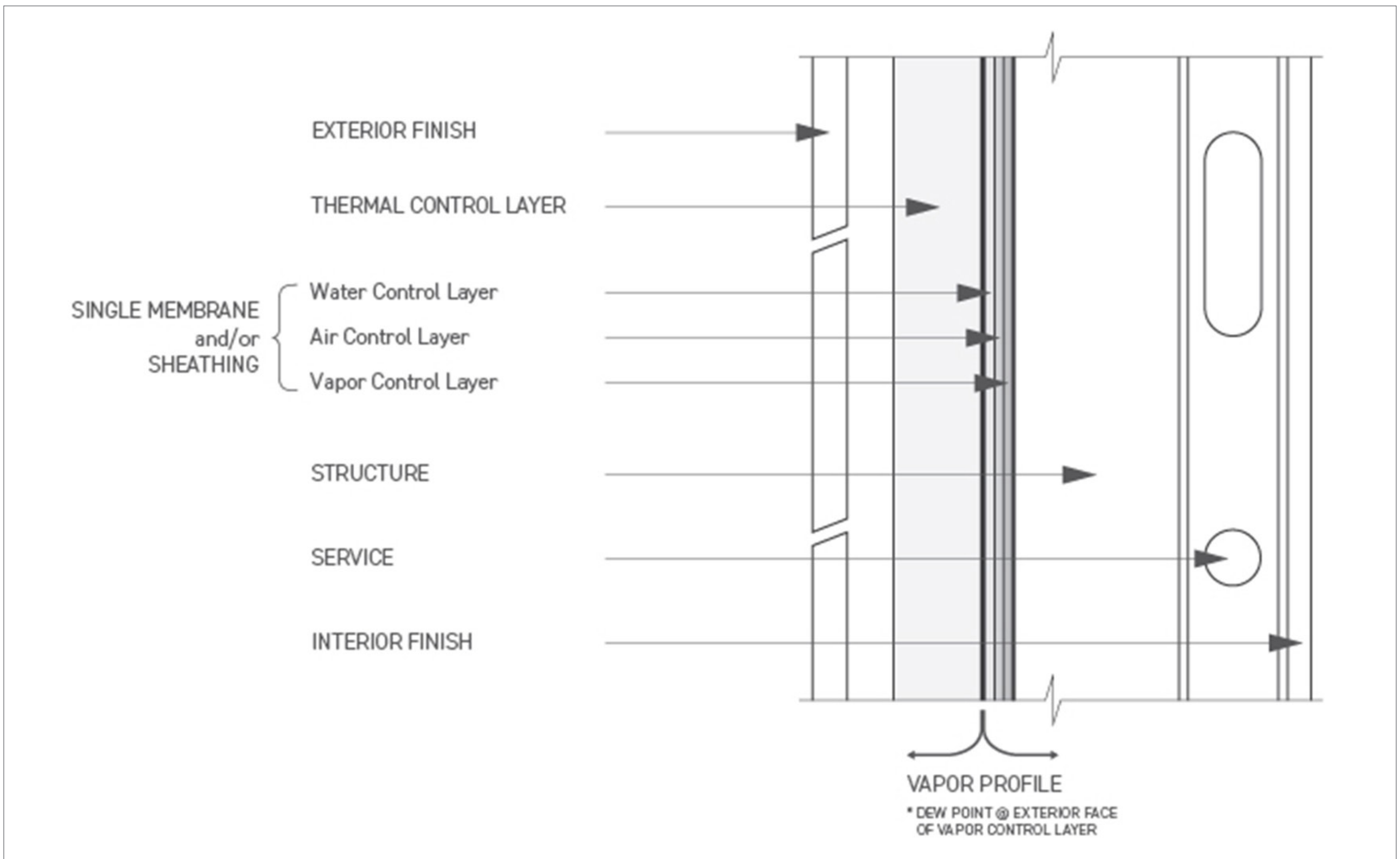

FIGURE 6 *Source John Straube, High Performance Enclosures, Design Guide for Buildings in Cold Climates, Building Science Press, 2012, page 27 and 250*

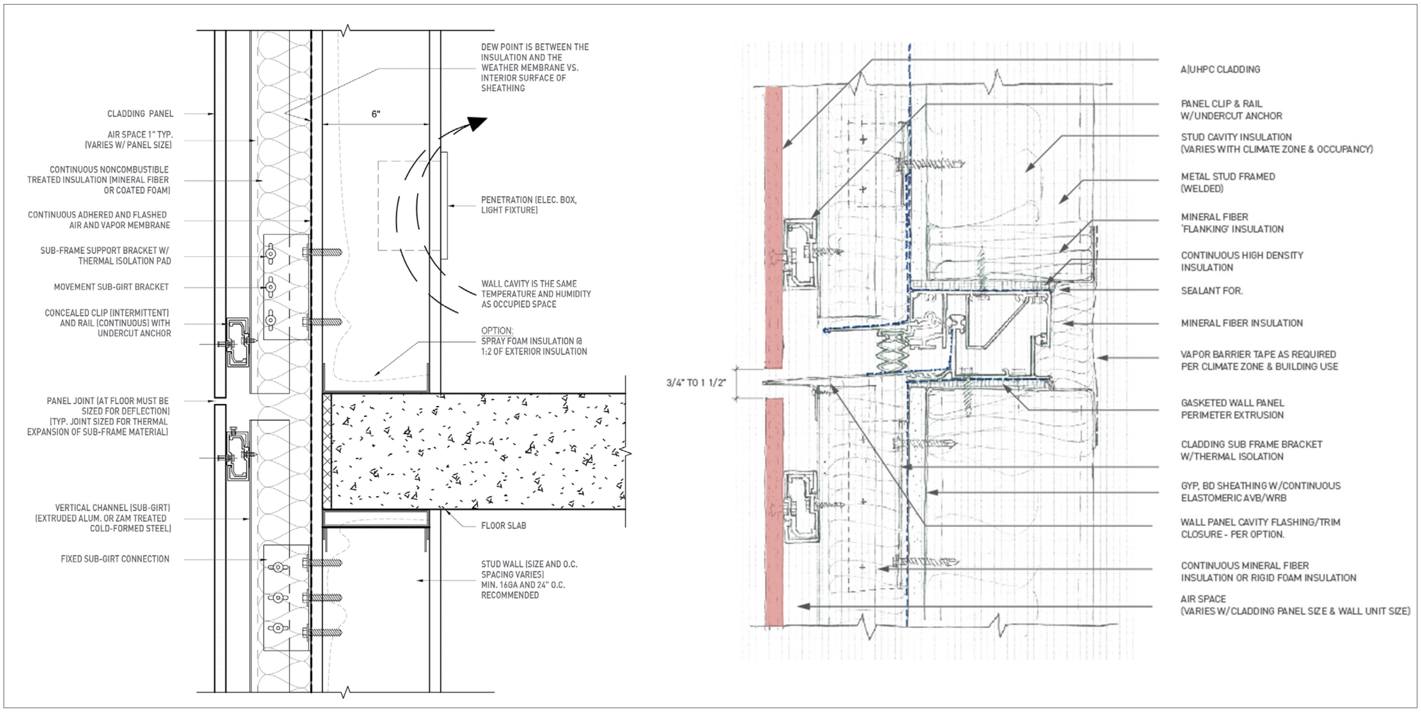

FIGURE 7 *(Left) Field constructed BVDC wall adhering to Straube's perfect wall, (Right) This shows the capacity of prefabricated BVDC systems to accommodate high R-values (R-30 shown here) while fitting A|UHPC panels with standard connecting hardware (including undercut anchors) in a configuration adhering to the principles of Straube's perfect wall.*

for insulation and air space. Using Climate Zone 5, the International Energy Conservation Code (IECC 2015) indicates a 'prescriptive' minimum for opaque wall insulation of R-13 +R-7.5 continuous insulation. Or, when using U-factor method, it is recommended to design with exterior Continuous Insulation dominating in conjunction with interior (stud cavity) insulation in proper balance to maintain the suitable dew point position at the exterior of the AVB/WRB. When the r-value of exterior insulation is 2x the R-Value of the interior insulation, the possibility of condensation occurring on the interior face of sheathing is eliminated. Therefore, careful consideration must be made for the balance of exterior and interior insulation. Factors for insulation amount and position vary with climate and occupancy. Moderate to very cold climates with higher interior humidity pose the greatest risk for interior condensation if the insulation on the interior matches or exceeds that of the continuous insulation on the exterior.

Advantages of Prefabricated BVDC Wall Systems include:

1. Using known frame, control layer, and proven systems in a more efficient way.
2. Capacity for Large Format, defined as 10' to 14' high and 20' to 30' wide.
3. Integrating glazing into the factory wall assembly, providing highly reliable seals and flashing for one of the most critical transition/interface areas of wall construction.

Other Materials in Prefabrication

Aluminum is often used to take advantage of the economics of extrusion, the non-corrosive property of the material, and the light weight of the material. Aluminum is highly conductive, with high thermal movement. Aluminum is commonly used for both fieldset installation of wall assemblies and prefabricated walls, and in each case the design and detailing of these walls must address thermal movement and thermal conductivity. The thermal efficiency of a unitized wall frame with aluminum is governed by the edge of glazing. In a BVDC wall the isolation of aluminum components from contact with structure behind the insulation control layer can significantly improve the overall performance of the wall. Typically, the stack joints (Unitized Curtain Wall or prefabricated BVDC walls) are not thermally broken, because the stack head must resist

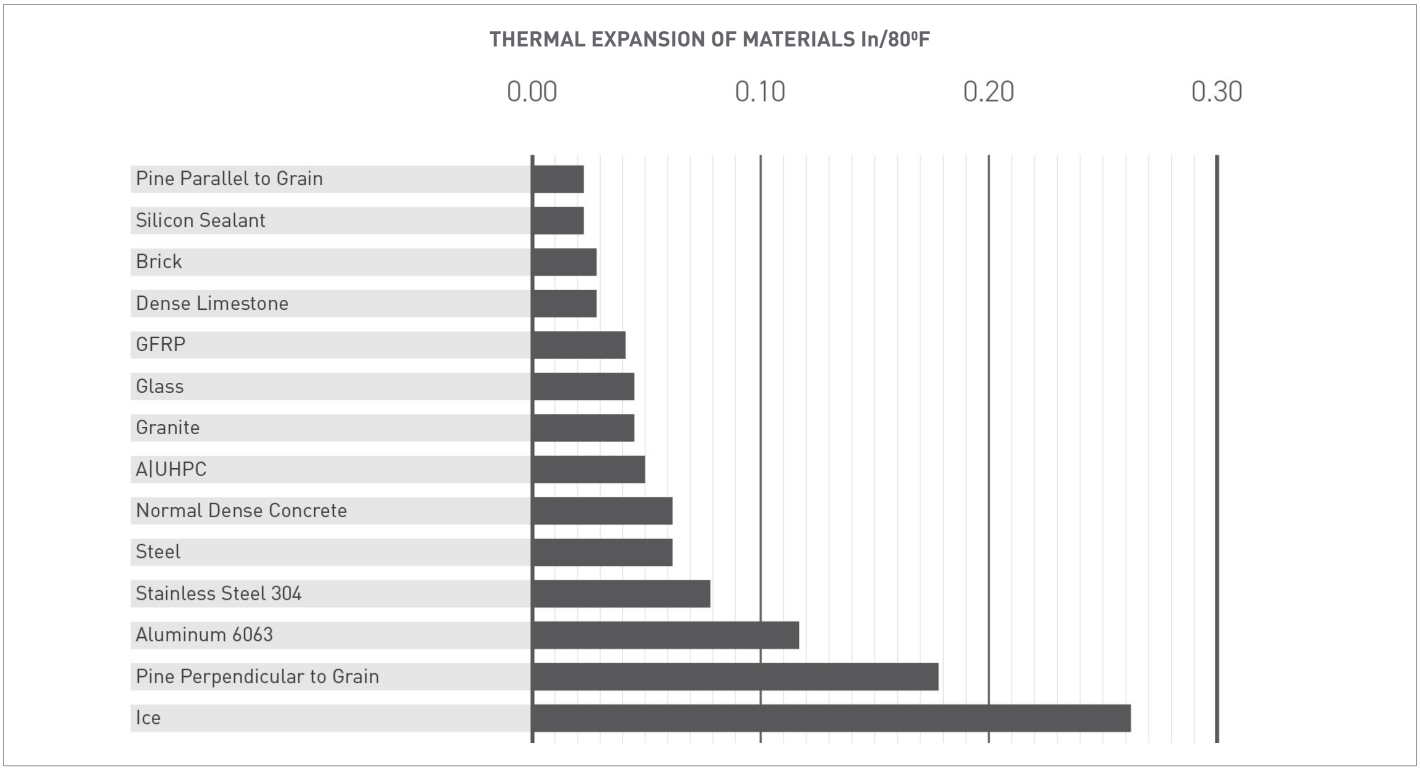

FIGURE 8 *Relative thermal expansion of materials used in unitized curtain wall and other wall systems.*

high lateral/rotational loads, and the materials available for thermal breaks are not reliable in this capacity. The edge of panel, either with a face cap or through structural silicone, provides a thermal break improvement; however, a pressure equalized rainscreen (PER) chamber exposes internal surfaces of the stack joint extrusions to outside temperatures and moisture. The flanking path at the unit perimeter or thermal bridge at the unit joint interface frame substantially lowers the overall u-value and at worst can lead to damaging condensation in cold climates.

Due to the thermal expansion coefficient differences —high for aluminum compared to glass—the aluminum frames must carry all the load transfer of the unit assembly. Accordingly, the potential composite action of panel and frame cannot be exploited. Structural sealants must be flexible, so they cannot be relied upon to create a composite action benefit that could reduce unit weight and wall depth.

Steel

The higher strength, lower conductivity, and competitive pricing of steel compared to aluminum give steel consideration for projects with special design criteria. Steel is very compatible with A|UHPC, since their thermal expansion coefficient values are so close.

Pultruded GFRP

Although the coefficient of linear expansion for GFRP is more than steel, it is compatible with A|UHPC for adhered composite elements. GFRP rods or reinforcing elements can be cast within UHPC just like steel reinforcing. With GFRP frames or joint closure components of a unitized CW system, low thermal conductivity and structural properties are the compelling characteristics for GFRP composite wall systems. Just as UHPC has made its way into architectural applications from a track record in civil engineering and industrial use, GFRP has made a similar path from proven uses in pedestrian bridges and industrial structural use to architectural use as a facade component. We can look forward to seeing A\UHPC and GFRP bonded together to work as a composite to achieve light, strong and durable facade components.

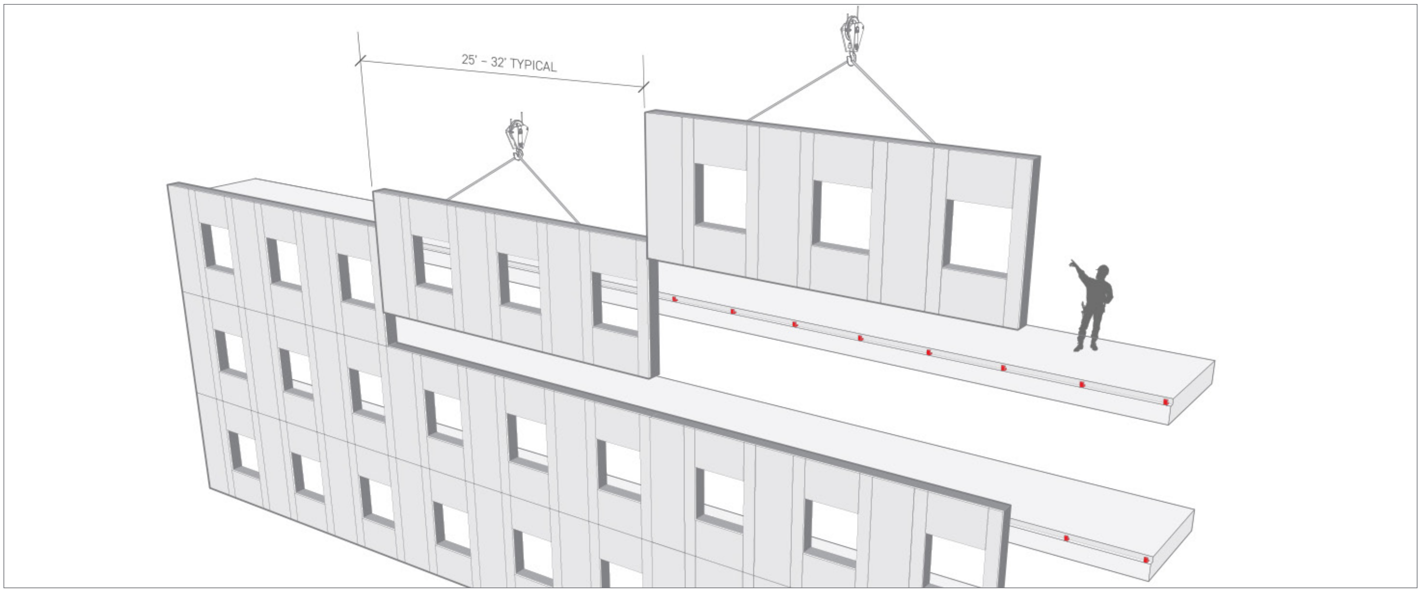

FIGURE 9 *Diagramic Install of Large Format BVDC wall system*

TYPES AND EXAMPLES OF UNITIZED WALLS

Prefabricated BVDC (Large Format Panelized Wall Systems)

Typically, these are light gauge metal frame (welded or mechanically joined) walls skinned with gypsum board and a weather membrane, open joint cladding, sub frame and continuous insulation in the cavity. The frame perimeter is gasketed and sealed, or the spandrel section is left accessible to field flashing and sealing the joint between units. Pre-manufactured wall sections can range in size from 8' X 10' up to 12' X 30'. Units are supported by a structural steel angle connection to slab edges and either welded or bolted in place.

Unitized BVDC curtain wall systems also have the capacity to maintain the essential functions and schematic layout of Straube's perfect wall, while altering the exterior profile to suit necessities of aesthetic and functional design. Because the continuous insulation is exterior to the water and air seal, A|UHPC panels, in their thin dimensions and light weight, along with their subframes, can be designed to change depth and turn corners, as well as to change aesthetic properties through a range of pattern, color, texture, and finish.

The potential of large format prefabricated wall systems is exemplified by the work of Handel Architects, Vidaris and Island Exteriors for a 26-storey Cornell Tech Dormitory on Roosevelt Island. 9ft tall and 36ft wide prefabricated wall sections with 25% glazing/75% opaque facade area are the keys to exceeding the PassiveHaus air infiltration standard by 75% (below the limit) and the building's energy budget at 73% reduction over the median EUI for New York buildings of similar type and size (Gonchar, 2017).

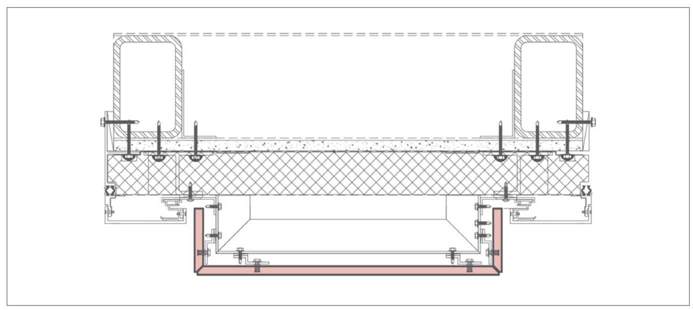

FIGURE 10 *Detail of BVDC wall assembly – unitized with projected cladding detail*

Unitized Curtain Wall with BVDC

A thermally broken, extruded aluminum frame with a gasketed perimeter has a sealed back pan. The unit depth holds cavity insulation, and the finish face of the unit is clad with A|UHPC panels with open joints. Panel attachment is either concealed with undercut anchors connected to clips and rails, or with direct, visible fastening to panel rails supported by the curtain wall unit

FIGURE 11 *A\UHPC cladding a Unitized BVDC integrated with glazing system. This example from a multi-use retail and residential complex in New York responds to the architects' desire for more expression of architectural depth on the facade of the building than the layers of the wall actually require.*

frame. Unit sizes can range from 4' X 10' up to 8' X 24'. These units are made similar to fully glazed curtain wall units, in that they have similar components and fabrication methods. The gasketed perimeter frames can virtually be identical to a glazed curtain wall unit in terms of the attachment to the super structure of the building, the perimeter gasketing, and the manner in which the unit is sealed for air and water. Although these units can incorporate both glazed area with opaque areas, our focus will be on the opaque clad unit, which is similar to the spandrel, with a key difference. One fabricator referred to these units as 'BVDC wall in a box', because the back pan provides the air and water seal, and the insulation is exposed to air and a small percentage of water through open joints. Depending upon the depth of the unit and the position of the stack joint connection for lateral load resistance, a thermal break can be introduced within the depth of the insulation, reducing the thermal transfer through the perimeter frame—the weakest part of the system that impacts the overall u-value of the unit.

One advantage for marrying the control layers of 'the perfect wall' with a unitized approach or a large format prefabricated wall system is that the compartmentation necessary for an effective pressure equalized rainscreen is built into the units and much easier and more reliably achieve than in field installed ventilated cavity walls with PER compartmentation. Another advantage of such units is the ease with which they can be incorporated into a facade with fully glazed units without introducing special transition details or new means and methods.

As shown in Table 2, A|UHPC has similar weight per square foot and flexural strength design values when compared to insulated glass units (IGU). This makes the engineering calculations for extrusions and frame capacities the same. The details for attaching glass and A|UHPC are the only difference. Using undercut anchors with extruded aluminum clips, the panels are dead load connected along the top edge of the panel and the remainder of the connection points serve only to resist the lateral wind load and are free to 'slide' to accommodate the linear expansion of the unit frame or in-plane displacement from storey drift.

University Of Alaska, Fairbanks

At the engineering building for the University of Alaska, Fairbanks, the unitization of the wall systems was employed, because of the severe climate, the very short season for working outside, and the need to enclose the building quickly to allow interior work to proceed fully protected. A few years ago in a more moderate climate zone, this project would likely have been field installed, given the building height. The project benefited from a local fabricator with a large enough facility to accommodate the assembly and storage of all of the finished units. The fabrication work was done over a period of months in the Alaskan winter and installed within a couple of months after the spring thaw.

In Fairbanks, Alaska, temperatures can range as much as 160˚F during the course of a year (-60˚ to +100˚F). Winter temperatures can stay at 40-below zero for weeks at a time. Accommodating issues related to such extreme cold puts considerable emphasis on design and specification of the building envelope. At the College of Engineering facility at University of Alaska, Fairbanks (UAF) (completed 2016), building performance issues were seamlessly woven into an insightful design that not only facilitates and showcases advanced engineering studies, it offers the building itself as a basis for student research and analysis. Building performance issues in

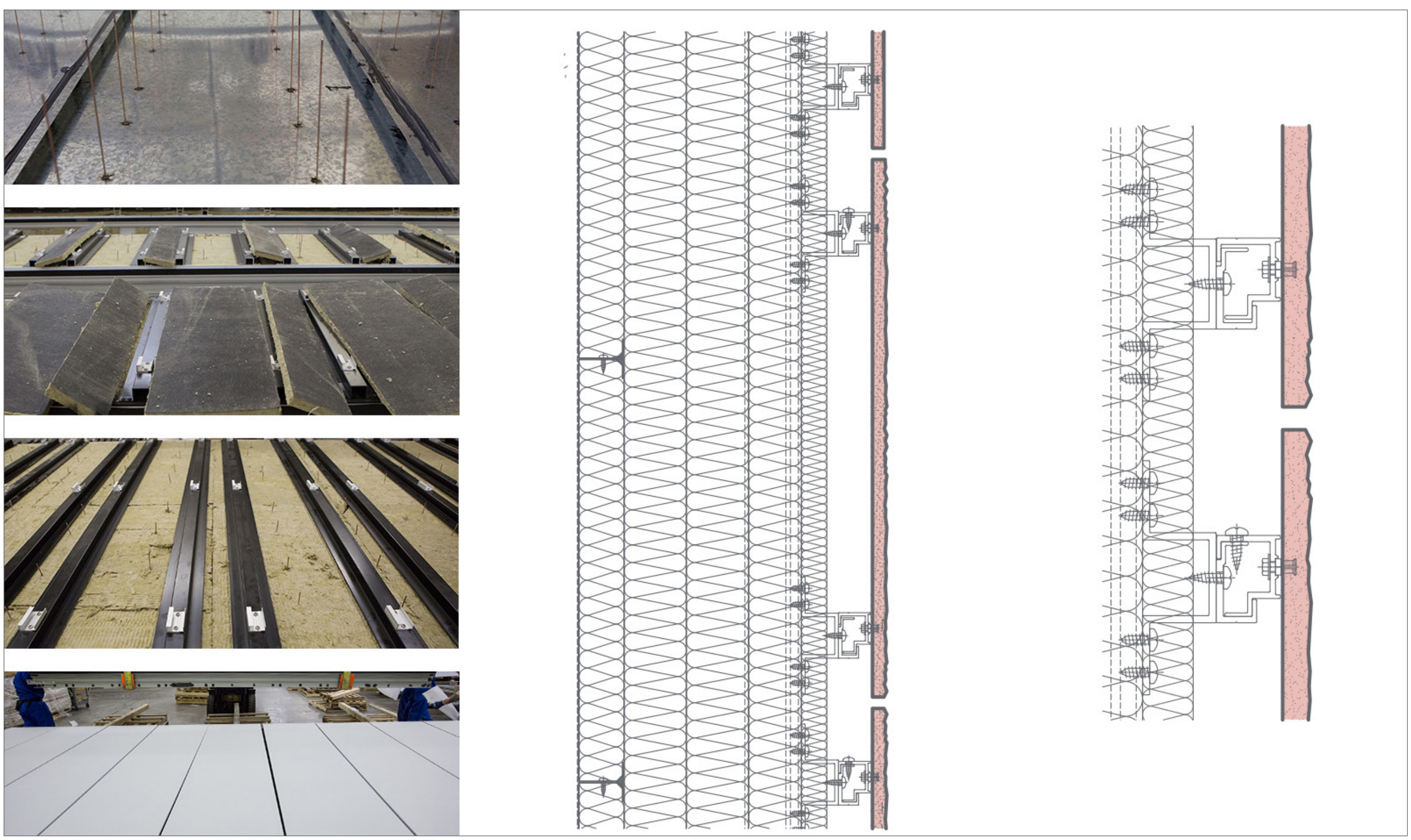

FIGURE 12 *For a project in an extreme Northern region (University of Alaska, Fairbanks), the wall section follows Straube's Perfect Wall diagram closely, with open joint panels and a ventilated cavity, though the insulation is exceptionally thick to respond to climate requirements. (Left) Assembly of control layers in BVDC curtainwall units, (Right) BVDC curtainwall*

Fairbanks go far beyond what is generally encountered in the Lower 48. Extreme temperature differentials from outside to inside—a 100˚ differential is not uncommon—can create pressure issues: a stack effect where the cold air is pulled inward with a high degree of force. In addition to a tight thermal seal and protection from air and moisture, the new engineering facility needed a cladding solution capable of withstanding periodic freeze-thaw conditions, dramatic annual temperature swings, material degradation via absorption and exposure, and corrosive factors such as salt spray from de-icing of the surrounding roads and walkways.

Many materials may become brittle and crack in persistent subzero temperatures. Expansion and contraction issues from metal cladding can harm the building's vapor seal over time. Moisture penetration in freeze-thaw conditions can also create degradation in many porous materials. Searching for a cladding material that could hold up in such demanding conditions, the design team began looking closely at A|UHPC facade panels. "When it comes to product selection, we look at the product performance at cold temperatures to make sure it performs," said architect Sean Carlson of ECI/Hyer. "We avoid any system that we can't get information about how it performs at 40-below." Bucher Glass and Overgaard, Ltd. Designed and engineered the unitized assemblies.

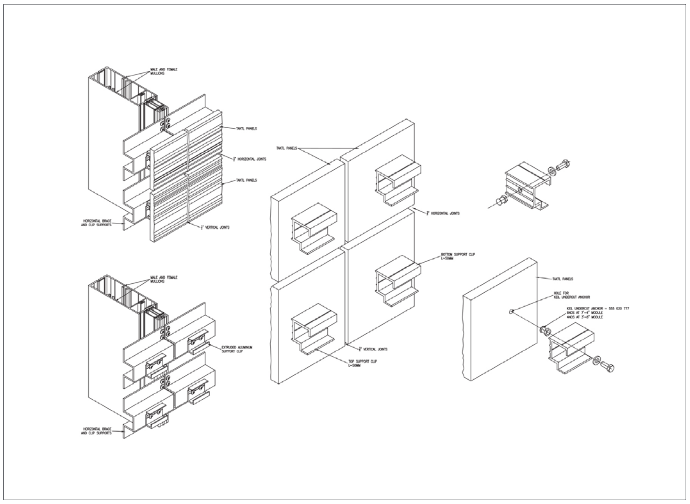

FIGURE 13 *Mounting hardware details show the fairly conventional c-clips and rails by which mounting takes place.*

TAKTL produced and delivered the facade panels, cut, finished, and drilled for concealed anchors. Fairbanks-based Bucher Glass fabricated and installed the CW units. Because the unitized panels represent a complete enclosure, the install was not only highly efficient, it allowed for increased control over the aggregation of tolerances that can occur with multiple trade contracts (primary wall, glazing, waterproofing, cladding). Field adjustments to fit the wall assemblies to the structure were handled by a single, expert installer, resulting in a streamlined installation.

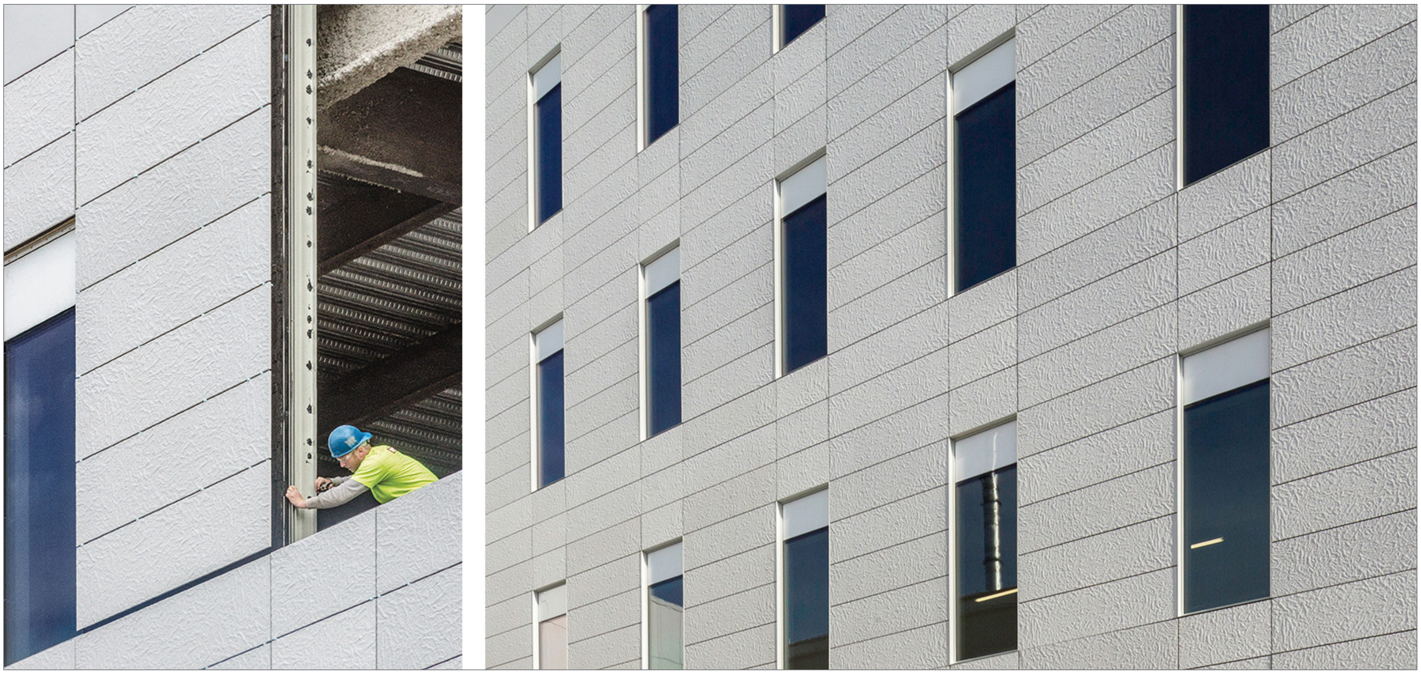

FIGURE 14 *University of Alaska, Fairbanks. A BVDC curtain wall unit shows open joint panels with an extruded aluminum perimeter frame.*

Hospital Complex (Midwest)

This project, part of a multi-block medical and hospital campus in the Midwest, has a wall system with slightly more complexity than that of the Fairbanks, Alaska project, but the approach to the curtain wall unit design is very similar.

The design takes full advantage of A|UHPC versatility. The majority of the enclosure is a multi-planar group of curtain wall units that integrates open joint A|UHPC cladding and back ventilated and drained cavity systems with a variety of more common curtainwall materials–insulated clear and fritted vision glass, connected to spandrel glass and painted aluminum composite panels. There are over 800 of these complex units on the project.

The A|UHPC is mechanically attached to the units using undercut anchors connecting to aluminum clips and rails. The units themselves encompass a breadth of techniques for making A|UHPC elements. These include integrally cast corners with custom ribs and patterns in a base thickness of 5/8" and overall dimension of 1 1/8", as well as mitered and bonded corners in vertical and horizontal configurations forming projected sills with fascia and soffit elements at a thickness of 5/8". In addition there are flat panels that are attached through the face with visible fasteners.

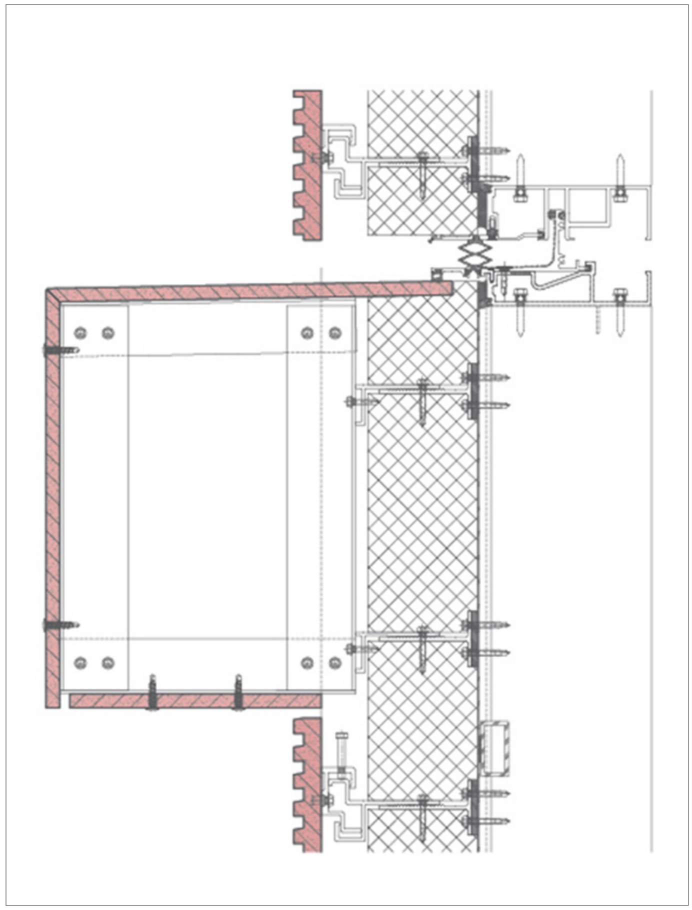

FIGURE 15 *Details of A\UHPC panel attachment to a BVDC unitized curtain wall, Midwest Hospital Complex*

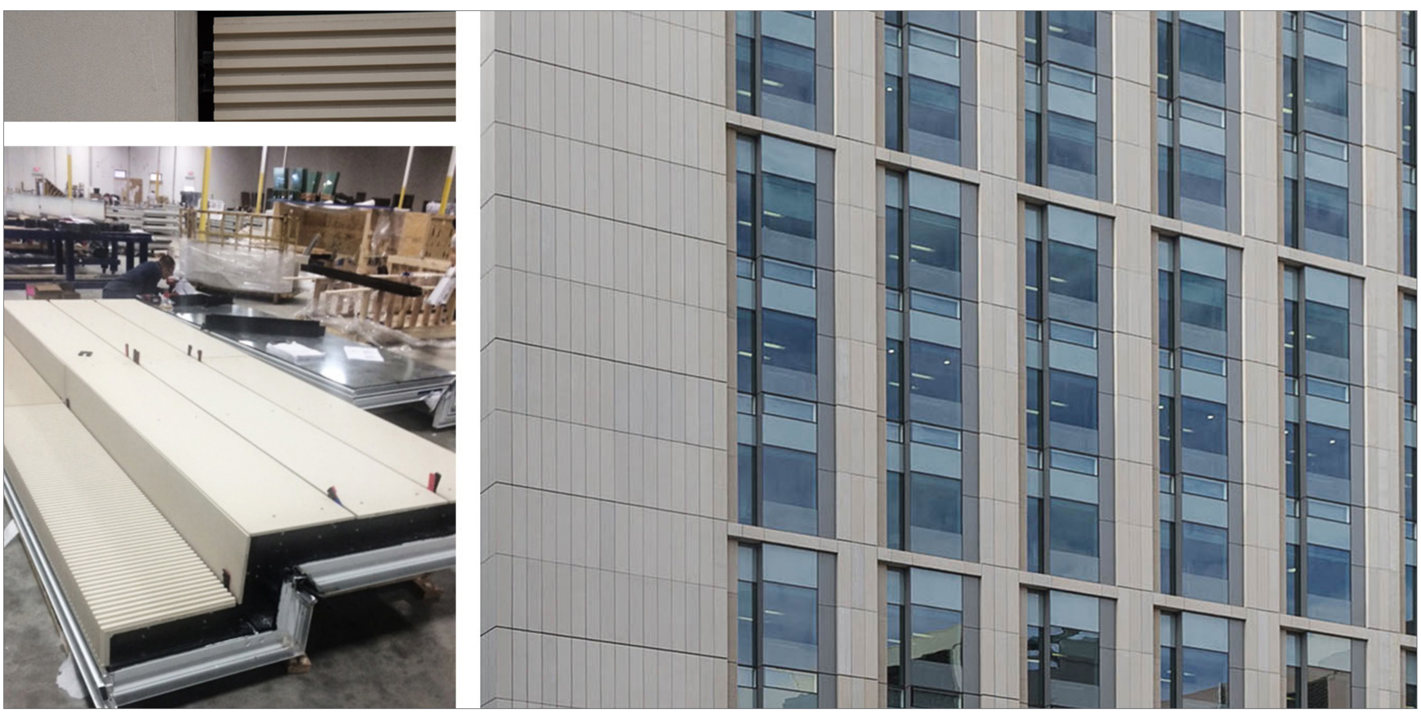

FIGURE 16 *Complex curtain wall unit + BVDC with A|UHPC cast corner and flat panel*

Commercial Building (Northeast)

Face Sealed Unitized Curtain Wall, Pressure Equalized Rain Screen (PER)

Very similar to the open joint example above, the system differs in its sealed panel joints and controlled weep vents. A continuous seal formed by two silicone gaskets at the panel joints forms the primary barrier to air and water. Any small amounts that penetrate the initial layer are drained through the profile of the aluminum extrusion, which also acts as a pressure equalizing chamber, preventing incursion any further through the wall section. This format may be constructed with an air space, front pan unit enclosure, and a back pan, or with the cavity open to the insulation layer. Panel attachment is either concealed, utilizing undercut anchors, clips and rails, or direct, with visible fastening to panel rails, supported by the curtain wall unit frame. Typical unit sizes can range from 4' X 20' up to 8' X 14'. The handability (size, thickness and weight) of A|UHPC is roughly the same as Insulating Glass Units, so Curtain Wall units do not need to be re-engineered for A|UHPC in an IGU system, where stone, at 1 ½ to 2" does.

Face sealed A|UHPC curtain wall units take advantage of ASTM standard C 1185 for water tightness (a panel sample with a perimeter seal is flooded a stipulated number of minutes with zero water absorption) and RILEM commission test No. 1154 (water column equivalent of 120 mph driven rain over a 24-hour period, with and without surface sealers, with no measurable absorption). Along with these water penetration/absorption tests, the warrantability for weatherseal adhesion, non-staining results with most of the common CW sealants (ASTM C1248) supports the use of A|UHPC panels for primary barrier use and wet-sealed joints. With this type of unitized application, linear thermal expansion is a factor, as the thermal movement of the aluminum frame is larger than the low thermal expansion of A|UHPC. The design considerations for joint sizes can be the same as glass.

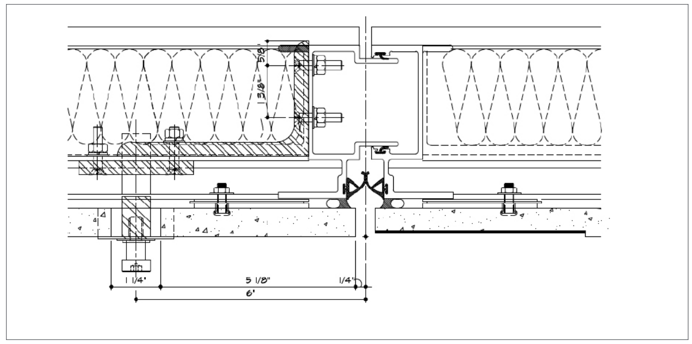

FIGURE 17 *Sealed curtain wall with A|UHPC mechanical fastening*

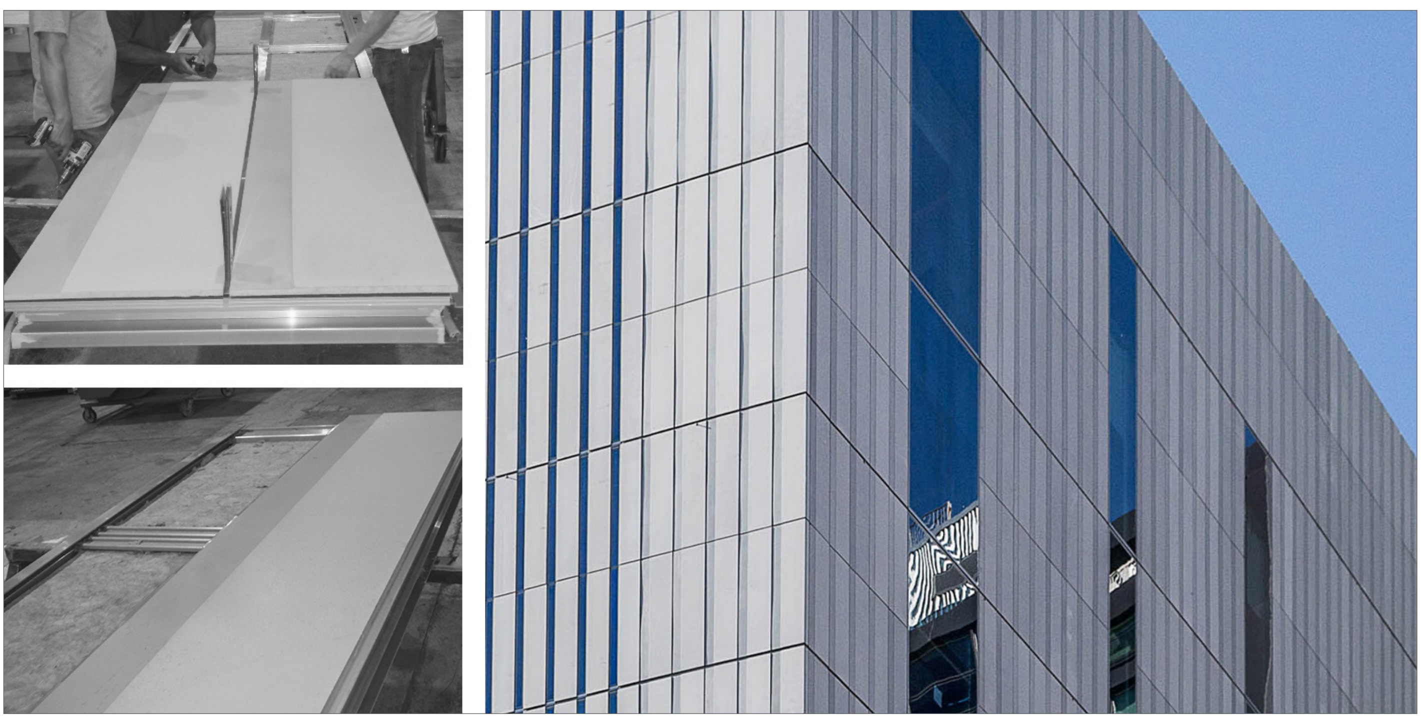

FIGURE 18 *Unitized Curtainwall with fully sealed joints*

The project shown is an office and retail structure in Lower Manhattan. On a primarily glass building enclosure, a section of opaque and narrowly fenestrated panels encloses building circulation and mechanical systems, while providing a material palette in harmony with contextual elements of stone and concrete. In this project unitized curtain wall panels with A|UHPC could be very similar to corresponding glass units. The Pressure Equalized Rain Screen configuration met the architects' specific request.

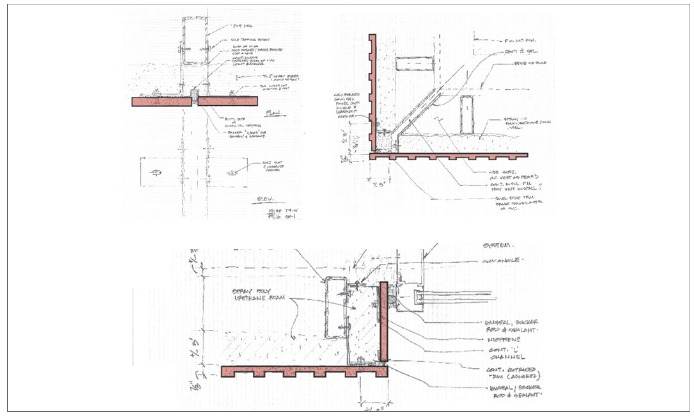

FIGURE 19 *A/UHPC large format barrier wall detail.*

Barrier Wall Cladding, Large Format Wall Systems

Characterized by a welded steel tube frame with mechanically attached A|UHPC cladding, this format has UHPC Cladding joints that are wet sealed in the factory. A|UHPC, as discussed above, is water tight and has tested compatibility with CW sealants. The example application below should be familiar to those with experience with spray-in glass fiber reinforced concrete (GFRC). The advantage of UHPC assembled in this manner is three-fold:

1. Strength/weight and the ability to work with a thinner/ lighter panel (5/8" thick A|UHPC versus 1" to 1 ¾" GFRC) Simple mechanical Attachment points are similar or fewer in number than GFRC – resulting in support frame efficiencies.
2. Tighter tolerances: panels are trimmed to size with CNC saws rather than dimensionally determined by mold and material shrinkage.
3. Cast shapes, surface textures and patterns can be made with more precision and less draft at the edges, as heavy chamfer or eased/radius edges are minimized.

The example for this format is the podium cladding for a mixed-use building in downtown San Francisco is collaboration with A\UHPC cladding manufacturer TAKTL and Willis Construction, a pre-cast concrete producer and erector. The original wall system specified by the architect was to be a field installed BVDC wall with A|UHPC panel cladding. When the Construction Manager faced restrictions in on-site staging as well as schedule pressures, they requested a revised solution. With a prefabricated barrier wall system in large sections, the building could be enclosed in a significantly shorter period of time with the least impact to other site operations or associated trades. The facade changed from a delegated design process involving the coordination of 4 primary trades to a design assist process coordinating only 2 trades (the prefabricated opaque cladding and the window wall system.) Multiple panels are assembled together with a welded tube steel support frame. All panel joints are double–sealed. Units are attached to the floor slabs or perimeter frame of the building and form both the primary weather barrier and the finish surface of the building envelope. Unit Sizes range from 6' X 12' up to 8' x 20'.

FIGURE 20 *Large format barrier wall*

NEW INITIATIVES

Structural Silicon - Opaque Curtain Wall Units

Similar to the applications discussed above, this Structurally Adhered Unitized Curtain Wall is characterized by an extruded aluminum, dry gasketed frame with a sealed back pan filled with mineral fiber insulation. In lieu of mechanical attachment, structural silicon provides the primary if not exclusive means of attachment and lateral load resistance connection.

For the reasons described above it is feasible to fabricate A|UHPC faced unitized CW units in the same manner as structurally glazed units–where the A|UHPC panel is attached to the unit frame utilizing structural silicone adhesives. However, the traditional view of 'concrete' products as porous materials has made a number of sealant companies hesitant to approve such applications, to the consternation of architects and CW fabricators. Adhering panels using the same products as structural glazing have been lab tested with good results—100% adhesion in accordance with ASTM C794 Peel Adhesion with water saturation cure conditions and intermittent testing up to 21 days. Full scale tests such as ASTM E330 and ASTM E331 are in the works. Full scale tests will be performed to establish initial proof of concept, followed by additional water and air seal tests with cycling, post-impact, and post-racking tests (AAMA 501.4) to support the implementation of such an advantageous unitized opaque wall.

Extruded aluminum curtain wall units with panels set/ attached in the same manner as structural glazing is an approach to building enclosure that has been requested by both architects and curtain wall fabricators.

This approach has economical advantages because, as previously noted, A|UHPC panels are water tight and weigh roughly the same as insulated glass units (IGU), so the preparation and labor to set panels in this manner are the same as with glass. This configuration also eliminates the material and labor associated with setting anchors, clips, and rails. Panel edge treatments and tolerances are key to the success of this approach. Likewise, silicone sealants and glazing adhesives have promising results. Unit Sizes range from 4' X 10' up to 5' X 14'. Taking this format to the next level of application

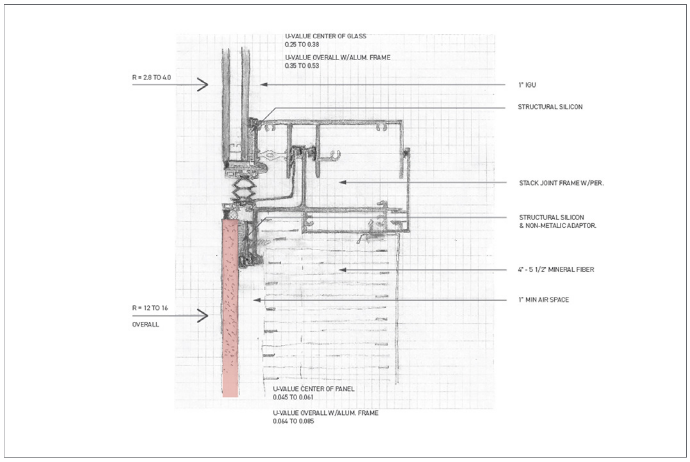

FIGURE 21 *Structurally adhered A|UHPC*

acceptance will require collaborative design and testing efforts with sealant products manufacturers, curtain wall manufacturers, and facade design professionals.

CONCLUSIONS

Pre-fabrication of wall systems and unitization of the building envelope will be more common for all building types and facade designs in response to construction economics, performance criteria, design complexity, and aesthetic preference. A|UHPC with its material characteristics and manufacturing methods presents an aesthetic and technical solution to a myriad of facade requirements that can be easily integrated into prefabricated wall systems; the development of new wall system solutions utilizing A|UHPC through collaboration with architects, facade engineers and wall system fabricators will continue to develop and expand the full potential of thin, Ultra High Performance Concrete as a crucial and contributing means to better performing buildings.

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