Designed for performance: A collaborative research studio rethinks glass curtain wall systems

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ABSTRACT: The growing demand for high performance buildings has pushed the architectural discipline to confront building performance as an integral part of design delivery, while increasing the necessity of collaboration between designers, building science experts, engineers, and manufacturers to find the best solutions to building performance challenges. This paper presents the research of a year-long architectural studio engaging a team of practitioners and outside consultants along with a major manufacturer of window systems. Student research teams were charged to rethink the modern curtain wall from the ground up, questioning its material, environmental integration, and manufacturing implications. Glazed curtain walls as a system have remained virtually unchanged for decades while great strides have been made to improve the environmental performance and durability of glass units. While the postwar industrial complex established extruded aluminum grids as the prevailing core of these systems, the research of the studio hypothesizes that new structural, material, and fabrication approaches can improve the environmental performance and architectural integration of curtain wall systems. Three experimental systems developed during the studio are presented in the paper, along with preliminary performance data showing their relative successes and shortcomings versus a contemporary high-performing curtain wall system. Prototyping, analysis, and simulation methods are also detailed. While the current body of research presented focuses on curtain wall systems, critical links are drawn between the research studio and practice with regard to how performance is evaluated and integrated as part of the design process of high performance buildings.

KEYWORDS: Envelopes, Performance, Simulation, Testing, Prototyping

INTRODUCTION

In the recent book Design Informed (Brandt 2010), Susan Ubbelohde and George Loisos talk about architectural problem solving in a performance-based practice as “one of the best ways to encourage innovation and creative response.” The challenge of designing high-performance buildings require architects to engage building science and manufacturing in a more direct way in the past, providing an opportunity to drive innovation by connecting performance objectives to emerging, integrated design strategies. Requisite to this level of engagement is collaboration in the design process among architects, building science experts, engineers, and manufacturers to find the best solutions to building performance challenges. Architects are uniquely positioned to understand the context and potential integrated response to such performance problems because the profession is situated between the technical aspects of the building and the multimodal performance objectives driving the project: objectives transcending the engineering of the building to address the larger ecology of the building’s environment, function, and service to its occupants.

Inevitably, the pursuit of performance problems reveals knowledge gaps in what is known about building behavior and building assemblies. Whether small or large in scope, these gaps in knowledge appear with acuity to architects engaged in the profession. In the past, knowledge and technological resources were not readily available to the professional (or the manufacturer for that matter) to explore every gap in knowledge encountered. Today increased availability of design and analysis software has coupled with new openness to collaborate across disciplines to make inquiry, analysis, and testing a potentially more integral part of everyday practice. In the last decade several firms have lead the rest of the profession in introducing research into practice: namely SOM, Perkins + Will, and Kieran and Timberlake.

This paper presents the research of a year-long architectural studio in the Department of Architecture at Kansas State University that engaged a team of practitioners from BNIM and PGAV (Kansas City architecture firms), outside engineers and specialist consultants, and Manko Window Systems in a research and design project during the 2014-15 academic year. Students working in teams were charged in the research studio to rethink the modern curtain wall from the ground up, questioning its material, environmental integration, and manufacturing implications. A major goal of the studio was to introduce students to a research approach in which building science concepts, experimental methods, simulation and analysis tools, and prototyping could be deployed, suggesting perhaps a knowledge base valued in a profession that will increasing be involved in research in the future. In this context the collaborating team of professionals and manufacturer provided real-world insight and feedback during the project.

1.0 CURTAIN WALLS: PERFORMACE CHALLENGES AND POTENTIAL SOLUTIONS

In the early phase of the studio, knowledge of the history of curtain wall system was assembled from a literature review and from interaction with Kevin Dix, the head engineer and Vice President at Manko, who contributed decades of experience in the commercial fenestration industry. Kevin and Manko's insight was also critical because as a small yet successful regional manufacturer, the company has actively developed its product line using the latest materials and manufacturing methods, while testing its products to residential and commercial AAMA and NFRC standards. Thus the engineering and production process of aluminum curtain wall systems at Manko is more influenced by the performance opportunities and tradeoffs than manufacturers whose limited product lines require less in the way of testing.

While visiting Manko's manufacturing facilities, it became apparent that behind contemporary glazed curtain wall systems are a collection of technologies that in some areas have developed aggressively, yet in others have remained unchanged for many decades. For example, glazing technology has evolved greatly, with manufacturers now employing highly precise, automated production of insulated glass units (IGUs). These vastly improved IGUs are manufactured with metered argon that is contained by new, highly resilient sealant and silicon (versus metallic) spacer combinations, and new coating technologies that reduced thermal transmission (U-Value) of mid-centurty double-glazed IGUs by a factor of over four, with the best performing systems achieving U-Values approaching 0.125 BTU/hr*ft^2*°F: a number very close to an opaque, insulated cavity wall. At a company like Manko the most significant recent production investments have been focused on the production of insulated glass units.

On the other hand, the aluminum frame systems used for stick and unitized curtain wall have remained virtually unchanged for decades, with the main improvements involving the use of better-performing gaskets and thermal breaks, specifically using polyamide and other advanced materials. Yet the basic system and profiles of aluminum systems persists, with manufactures offering nearly identical products. A few explanations exist for this stagnation in technology that illustrate the timeliness of innovation in this field. The first explanation involves intellectual property: PPG, a major player in the glass, coatings, and curtain wall industry, abandoned curtain wall production and sales in the 1980s. Subsequently their designs and extruding dies became free-to-use 'house dies' for other aluminum extruders in North America, offering established engineering and manufacturing infrastructure and becoming the template for the ubiquitous aluminum curtain wall profile of today. The second explanation behind the establishment of aluminum curtain wall is an historical one. The historian David Yeomans attributes the development of the aluminum curtain wall to the postwar industrial complex, which sought to repurpose the aluminum extruding capabilities from the construction of warplanes for domestic production (Yeomans 2001). Yeomans argues, additionally, that curtain wall development was driven not merely by the aesthetic of glass, but by the utility, durability, and economic efficiency of these modular systems whose initial deployment was in factories, retail buildings, garages, schools, and laboratories (Yeomans 1998). Simplicity and utility drove the evolution of these systems and these objectives have been met well by the familiar aluminum extrusions.

Paradoxically, attempts at revolutionary improvement to these systems in the 1950s and 1960s never stuck. Yeomans discusses an author and researcher named Robert Davison, an early advocate of aluminum curtain wall systems who through the 1930s to the 1960s fervently promoted the idea of insulated metal panels as a way to improve thermal performance of these systems (Yeomans 1998). Davison's essays on this subject show no shortage of technological vision, discussing aerogels and exotic foamed materials decades ahead of the green material surge of the 21st century; it is also worth noting that Davison's vision for these systems focused on the economy and function of vernacular applications rather than the monumentality of glass (Davison 1947).

One of the major performance challenges of the glazed aluminum curtain walls is thermal performance, with both aluminum frames and glass infill having high thermal conductivity and the sealing and gasketing of the assembly required to ensure airtightness. The issue of embodied energy in aluminum is also complex, because while aluminum commonly contains a high amount of recycled content, the use of anodized coatings in curtain walls requires that aluminum is high quality 'virgin' aluminum. The production of glass is also energy intensive, with large amounts of energy consumed in glass production and the significant creation of waste from glass pre-production, breakage during shipment, and the expiration of inventory due to factors such as the oxidation of low-E coatings. A last reality of curtain walls is that the final curtain wall performs only as good as it has been installed; in in particular the interfaces between CW and other walls are not tested as part of the systems' ratings and can be a major source of performance problems (Boyle 2013).

Yet the opportunities presented by glass and aluminum curtain walls are positive. First, these systems can be very affordable, with straightforward erection and expectations for performance (thermal and otherwise) in comparison to layered walls using materials like veneer stone and brick with insulation in cavities. Secondly, the use of glass presents particular risks for condensation, when the interior glass surface drops below the dew point temperature of the interior environment. Thermally-broken aluminum framing systems help to maintain temperature isotherms through the glass IGU by transferring heat to the edges of the glass, where it is covered up by the aluminum frames. Quite by accident, an early experiment by a student group replaced the aluminum framing with wood mullions; the wood mullion insulated the edge of the glass from the interior, allowing heat loss to occur laterally along the glass, dropping the glass temperatures at the edge of the simulated assembly and suggesting an acute condensation problem. In summary of these points, glass units and aluminum frames work together well to address issues of constructability and condensation.

Another important advantage presented by these systems is one of airtightness, although traditionally fenestration systems were perceived a weakpoint in the building envelope. A recent assessment of the role of infiltration in energy use of commercial buildings (Emmerich 2005) developed a target infiltration rate used for energy models of 1.2 L/s-m2 (0.24 cfm/ft2) @ 75 Pa (1.58 psi) based on modern construction data with a 'best achievable' infiltration rate of 0.2 L/s-m2 (0.04 cfm/ft2) @75 Pa (1.58 psi); in this paper, only 6% of a set of existing buildings tested met the target standard for infiltration. The same study estimates that reducing infiltration rates in commercial buildings to the target rate would save 40% in gas savings and 25% in electrical savings in heating dominated climates (Emmerich 2005), indicating that one of the most significant challenges in meeting efficiency targets comes from building airtightness. Yet modern wall and fenestration systems promise extremely tight assemblies: where is the problem? Modern efforts with building envelope commissioning has identified that the typical source of infiltration in buildings is not within the wall or fenestration systems in the envelope but at the interfaces between them where air barriers must properly transition (Boyle 2013), which are particularly acute in buildings with punched openings. One may surmise that a solution to the problem of infiltration is to adopt a reliably tight system and transition between glazed and opaque walls within that system. The triple glazed curtain wall system available from Manko infiltrates at 0.06 cfm during a test at 6.24 psf; if the system could maintain such tightness continuously across an entire building envelope it could easily perform below the targets cited in Emmerich (2005). Albeit this comparison is based upon different tests (whole building infiltration versus assembly infiltration) and doesn't address the challenge of establishing continuity at floors, roofs, and other challenging areas; yet it is possible that high performing glazed curtain wall systems could be an important component to improving energy efficiency when infiltration is critical.

2.0. STUDIO RESEARCH PROCESS AND METHODS

Proceeding from background research and interactions with Manko, the research studio's goal was to develop new curtain wall systems that recognized the advantages of tightly-sealed high performance glass but reconsidered how the glass would be integrated in a curtain wall to increase overall efficiency with respect to energy. This paper presents a comparison of Manko's highest performing system with three experimental systems developed and tested by the students. The system from Manko is a thermally-broken 2.5-inch profile curtain wall system using triple glazed, argon-filled IGUs: one of highest performing curtain walls available for commercial projects.

Students worked in teams of three to develop and test their experimental systems, modeling a progression of testing methods inspired by the methods used by Manko. Development began in a "what if" stage where teams developed basic hypotheses about system performance and the physics supporting the efficiency assumptions for their systems. Material and structural capacities were interrogated during this phase, with the groups proceeding to model and simulate their hypothetical systems using THERM and WINDOW simulation tools from Lawrence Berkeley National Labs. THERM and WINDOW test two-dimensional sections through walls, frames, and window glass using finite element analysis to predict temperatures throughout the test section as a result of multiple modes of heat transfer, using prescribed boundary conditions (i.e. environmental conditions) at each side of the wall. Because the NFRC uses this software in its certification process (ANSI/NFRC 100-2014), these simulations allowed the research teams to compare their systems to Manko's official NFRC certification models using the same simulation configuration and boundary conditions. At this stage student groups also tested a number of alternative hypotheses at a time, using failed ideas to inform decisions about how to improve the performance of successful ideas. Using THERM and WINDOW early in the process took advantage of the relatively quick turnaround and low-risk associated with computer simulation, something also done at manufacturers like Manko to vet new product variations and improvements prior to prototyping.

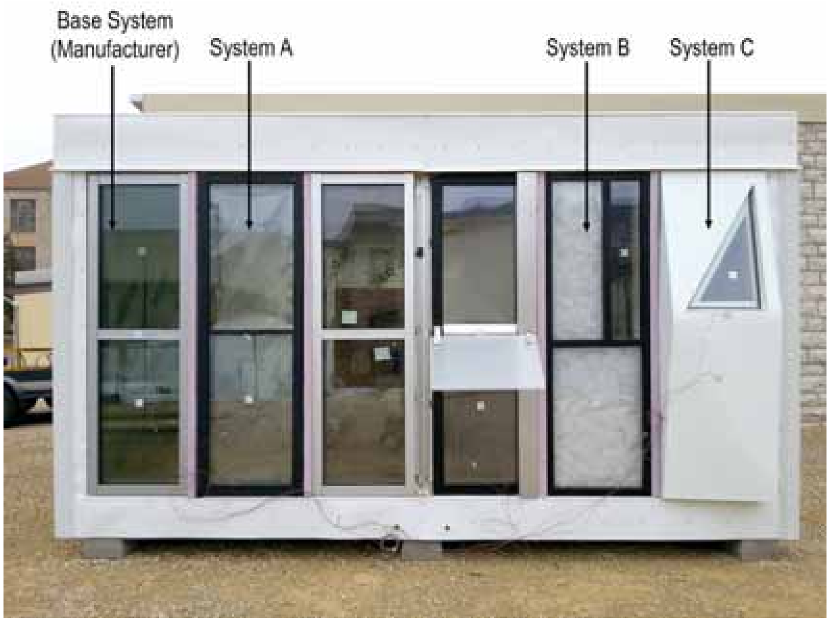

Figure 1: Image showing test structure and 1:1 scale prototypes constructed by the students for thermal testing. Source: (Author 2014)

Following the development of experimental systems in THERM and WINDOW, students worked to extrapolate thermal properties outputted in THERM and WINDOW (such as U-Values, Solar Heat Gain Coefficients, and Visible Transmittance) into Autodesk Ecotect whole building energy simulations using a studio-wide test model. The test model represented a skin-load dominated office building of 24,000SF located in Des Moines Iowa with IECC prescriptive envelope properties and 38% glazed wall area and included internal and ventilation gains according to IECC guidelines. This effort allowed students to determine the monthly, seasonal, and annual impact of their experimental systems as part of a realistic, hypothetical commercial building.

The last phase of development was the production of a series of two prototypes, built at 1:1 scale. The first prototype was a 'desktop model' that served as a proof-of-concept during discussion with the collaborating manufacturer and architects. For this model, students set about addressing issues of fabrication and assembly that are inevitable when moving from virtual models into real physical objects that must negotiate imperatives of construction. Feedback from the small prototype and the simulations ultimately led to the design and fabrication of a larger 1:1 prototype that each team completed to fill a 27 inch wide by 74 inch high rough opening. These large prototypes were completed using material and assembly techniques that were as realistic as possible, with IGUs and curtain wall hardware supplied by Manko. In addition to the five student-developed prototypes, a curtain wall unit was assembled by Manko at the same dimension. Together these six curtain wall sections were installed in the southern wall of a test enclosure measuring 16 feet long, 8 feet deep, and 8 feet high which was erected on a gravel pad outdoors with maximum exposure to the south, southeast, and southwest. The envelope (walls, floors, and ceiling) of the test enclosure was finished with 3.5-inch Raycore Structural Insulated Panels with an additional 0.75 inches of polystyrene insulation over the exterior (see Endnotes 1 for more information on test house construction). Constructing the prototypes and using them to test real world performance is the procedure used by Manko because real world multidirectional heat transfer, assembly-related problems, and infiltration cannot easily be tested using virtual prototypes. Conventionally these tests would also be carried out for water penetration and structural resistance; however, the studio chose to focus on thermal performance.

Data collection carried out in the test enclosure included continuous monitoring of normally aligned interior and exterior surface temperature points at select sites on each prototype, along with temperature of interior and exterior environments and instantaneous thermal imagery collected with a thermal camera. Temperature data, collected by thermocouples and data acquisition devices, was used to calculate continuous and averaged heat flow rates at the interior surface of the test sites. The equations and instrument configuration for thermal tests are described in the endnotes. During tests, a small, thermostatically controlled space heater was used to maintain a relative interior temperature in the test enclosure, with a set point roughly at 68F. The space heater was directed away from the curtain wall prototypes in the interior and because of the small size of the space heater, forced convection had a negligible effect on the individual prototypes and sensors. Data was collected to establish a baseline infiltration (air leakage rate) for the entire enclosure. In series, each individual prototype was tested for infiltration by masking off the other prototypes; per ASTM standards infiltration testing focused on leakage within the window unit rather than around the outer frame, and perhaps related more closely to the continuous condition of a curtain wall system rather than the extreme edges. Experimental setup and data collection for tests is described in greater detail in the endnotes. Overall the fabrication and full scale testing of the experimental systems served to confirm the viability of the systems against real-world conditions and concerns.

3.0. EXPERIMENTAL SYSTEMS AND FINDINGS

Three experimental systems and the base system from Manko are compared in this paper, with descriptions of each system, their conceptual bases, and a discussion of findings from simulation and testing:

3.1. Base System: 250i system from Manko window systems

The system provided uses aluminum frame using an internal polyamide thermal break to fully isolate the exterior pressure plate and cap from the interior frame. The glazing unit used was a triple glazed, argon-filled IGU using Low-E glass and structural silicone spacers and a factory edge seal, installed with EPDM gaskets on interior and exterior in the curtain wall frame (Fig 1). Joints in the assembly of the frame were friction-fit with factory-supplied hardware and further sealed with silicone. This system represents the thermally highest performing system available from the manufacturer but generically represents a top-of-the-line glass curtain wall that is becoming more widely available.

The performance of the base system is discussed in the comparisons of experimental systems below. It should be noted that the base system was assembled in the factory by an experienced fenestration contractor as part of a demonstration organized for the students, while the experimental systems were devised in part or wholly in the college shop. It should be noted that Manko's system set a very high performance bar particularly for infiltration with nearly immeasurable leakage in testing.

3.2. System A: Structural spacer in insulated glass units

This system was developed by a team that acknowledged the curtain wall frame's cross section (and the aluminum contained in it) typically isn't used to its full structural capacity in the horizontal direction, while it merely transfers loads from the glass to the vertical mullions which justify the full geometry of the frame for structural reasons. Additionally the team recognized that with high performance IGUs, it was often the frame that had the lower thermal resistance; eliminating any part of the frame could increase the overall thermal resistance of the system. The response developed by this group was to integrate a steel member in the horizontal orientation in the IGU which would also serve as the spacer on those edges. The team recognized that this would require slightly denser spacing for vertical mullions, since the span of the steel member would be limited structural. The spacer designed by the team is capable of spanning 6' in a 24 sq. ft. IGU according to structural calculations for resisting dead load and wind loads and given the allowable deflections in the glass and adhesives. Secondly, the team's IGU requires two internal films in the glass cavity to prevent convection. Computer simulations were carried out with the IGU using an argon fill and Low-E films, while the prototype constructed by the team was filled with air and used uncoated Mylar films. The frame designed by the team integrated a steel shelf that was bolted to the frame prior to installation; assembling the system required setting the IGUs on the shelves and using conventional pressure plates and covers to complete the installation. A compressible foam gasket was used in the horizontal joints between IGUs, and the interior and exterior joint was sealed with silicon as a final step.

Figure 2: Manko's 250i system with triple glazing and thermal break (left) and System A prototypes and thermal simulation. Source: (Author 2014)

Virtual testing in THERM indicated an increase in thermal resistance of 59% compared to the base system, a significant improvement (Table 1). It appears that much of this improvement comes from an elimination of surface area at the frame where mullions have been eliminated; though the thermal resistance at the structural space actually decreases, this is locally a much smaller area for heat transfer than the conventional mullion. Improved thermal properties were then simulated with whole building energy modeling (Autodesk Ecotect) in a 24,000SF commercial building. In comparative simulations, combined HVAC energy usage was reduced by 17% by using this system versus a high-performing double glazed system. Secondly, the research team also used Ecotect to simulate the improvements to daylight factor offered by their system versus the base system; in a room with a 2:1 depth to height ratio, daylight factor increased 20%.

In the prototype testing, the system performed quite well despite some compromises in the prototype materials: namely in the improvised IGU, which used uncoated Mylar rather than a low-E coated film, and also used air in glass unit rather than argon. Despite these compromises the glazing unit performed very closely to the manufacturer's base unit, with interior temperatures and heat transfer rates within only slightly increased over Manko's. The temperatures at the center mullion were much lower for the prototype than the manufacturer's unit, as predicted by THERM; however the site of increased heat transfer was highly localized when viewed with thermal imagery. While not measured, light admittance and view through the small prototype was increased notably in comparison to the more bulky conventional center mullion in the manufacturer's unit. This prototypes leaked through the improvised IGU during infiltration testing, producing deflection in the Myler interlayer; this prototype's air leakage results could be improved, and even so, the system was tighter than the test enclosure (Table 3).

3.3. System B: Composite node system

A team of students developed the composite node system in response to two strategies. The first addressed the availability of relatively low cost, multiwall plastic products that are less conductive than glass but retain translucency and daylighting potential. These products are used in place of glazing quite frequently in commercial curtain wall systems; however the light weight and relative affordability of the plastic can allow it to easily be deployed in a double-wall system. Coincidentally some manufacturers of multiwall plastic offer such solutions. In response to this concept, the team developed a framing system that would allow for a deep section (for thermal resistance) that could accept a multiwall polycarbonate skin on both interior and exterior sides. Within the section, translucent polymer fiber insulation fills the gap. The second issue addressed in this system is that of thermal transmission through the aluminum framing. To respond to this problem the team devised a framing system consisting of interior and exterior 'rails' that interface with either polycarbonate or glass IGUs with conventional curtain wall pressure plates and cover caps. Between the framing rails, composite nodes intermittently tie the rails together and allow connections throughout the systems and to the building. The ingenuity of the system is that it allows conventional vision IGUs and operable windows to be introduced freely within the system. Weather stripping, mechanically installed pressure plates, and conventional sealants complete the air and water barrier on the exterior face while the interior wall would be unsealed to prevent venting and equalization of vapor from within the wall cavity.

One of the most important implications of this system is that aluminum is used in an advantageous manner – to create a resilient, easily erected wall system – yet the amount of aluminum in the frame is reduced by using the rail and node system in place of larger and heavier rectangular profile reducing thermal transmission. Additionally, most of the aluminum in the system (except the caps) is inside the wall; this would allow the system to use a non-appearance grade of anodization for the rails, allowing the use of recycled aluminum instead of virgin aluminum.

Figure 3: System B diagrams and thermal simulation (left) and System C prototype and thermal simulation (right). Source: (Author 2014)

Simulations in THERM show that thermal resistance of the infill system with a 6" deep cavity would increase by a minimum of 65% at node connections to a maximum of 84% in the cavity areas of the system (Table 1). Whole building energy simulations were then used to compare performance of the 24000SF test building using this system versus the manufacturer's base system; calculating an aggregated U-Value for a composite wall of 20% glazing and 80% polycarbonate infill, the building HVAC energy usage is reduced by 20%. The team also conducted several daylight simulations using Radiance to evaluate the impact of their system for daylight diffusion, distribution, and glare prevention.

The team constructed their prototype after developing a series of smaller models to refine the design of the rails and nodes, especially the connecting interfaces. The final 1:1 prototype used improvised aluminum rails composed of curtain wall 'Ts' – a profile without the structural box. The Ts were then welded to extruded aluminum Ts to create a profile approximating the dimensions and stiffness of the rails designed by the team. The composite nodes were constructed from glu-lam beams that were milled and machined in the shop. Because the node design allowed a single node shape to be used for any of the connections in the system, fabrication of the nodes was very easy. As constructed, the system used polycarbonate from a local hardware store for the skin, loose polyester fiber to insulate the cavities, along with an IGU, caps, pressure plates, and weatherstripping provided by Manko. Performance of the system in real conditions was remarkable, with the interior polycarbonate skin remaining near environmental temperature and at a much higher temperature than the base system's glazing throughout the test. The interior frame cap also showed a reduction in thermal transmission, matching the glass temperature of the base system and reading warmer than the base system's frame. In summary the testing of the prototype confirmed expectations from computer simulations and showed that the main strategies of the system to reduce thermal transmission were working as expected. Infiltration tests were telling as well, with infiltration rates much lower than the SIP envelope of the test enclosure and lower than other group's prototypes (Table 3). While not as tight as Manko's system, this prototype had many more parts and opportunities for leakage and yet performed well, demonstrating that the depth of the system and redundancy has a payoff in tightness.

3.4. System C: Structural foam composite

The final system discussed in this paper was developed by a group interested in unitized curtain walls: those differing from stick systems in that the units are assembled in controlled conditions in the factory and set as units in the building façade. Other interests of the group included construction via 'grand blocks' as that used in the fabrication of large ships, and non-linear construction, where assembly or disassembly sequencing can be flexible and future modification and service is simplified. The group began with the assumption that in high performance buildings, a tightly controlled glazing area suggested a different approach was required than that used in aluminum framed curtain walls that use infill panels similar to insulated glass units. The solution developed by the group after some experimentation and research was that a high-performance foam panel could both support vision and operable glass, while also distributing loads from the panel to attachment points. Simple calculations confirmed that structural foam products have enough structural capacity to support large IGUs (50SF and larger) so long as minimum foam areas are maintained around the perimeter of the glass. Such foam panels can reduce the weight of conventional glass and infill panel systems by 60%, reducing construction equipment requirements and emissions in transportation.

A secondary concept that evolved with this system was a design for cam locks that could draw the panels against the floor perimeters of a building, compressing integrated gaskets around the perimeter of each panel. Additional locks could complete gasket seals at adjoining panels. Light weight, it turns out, creates the possibility of using such a mechanism; presumably these mechanisms would produce a continuously tight, thermally resistant envelope that could be easily modified or repaired by removing and replacing panels.

The final 1:1 prototype produced by the group used CNC-milled extruded polystyrene foam as the core of the panel, substituting actual structural foam with polystyrene with similar thermal properties. The panel varied in depth throughout its area, testing the groups assertion that this fabrication method would be conducive to applications where an ‘active Z-axis’ was useful either for structural, environmental, or aesthetic purposes. A single IGU was installed in the panel using structural sealant. Detailing around the IGU exhibited the group’s solution to condensation risk at the perimeter of the glass, where thermal resistance would drop precipitously from the conductive glass to the jamb opening, resulting in a low-temperature line along the glass interface. The group solved this problem by creating a lapped area at the perimeter of the glass where it could be adhered directly to the panel assembly, reducing the number of parts required in the panel. The exterior of the panel was finished in heat-bent fiber-reinforced plastic and applied with a liquid adhesive; the interior was finished with maple-veneered plywood and is removable to access connections.

In the computer simulations (Table 1) and in real-world testing of the prototype, this system showed a very high degree of thermal resistance in comparison with other systems tested. This is not surprising because of the depth of the panel. Temperatures at the panel surface were nearly identical at the thinnest (4”) and thickest (12”) part of the panel, suggesting diminishing benefit of additional foam thickness beyond 4 inches. Coincidentally the glass IGU, a double-glazed Low-E unit, recorded colder temperatures than other glass in the test, suggesting the properties of the surrounding panel may actually be increasing heat transfer at the glass unit. Whole building energy simulations were then used to compare performance of the 24,000SF test building using this system versus the manufacturer’s base system; calculating an aggregate U-Value for a composite wall of 25% glazing and 75% opaque infill, the building HVAC energy usage is reduced by 12%. The performance of this team’s system is highly design-dependent and in a building where the spatial and functional impact of the wall is favored over glazing, greater energy reductions could be realized. Predictably, the monolithic nature of this system performed well in infiltration tests, showing no measured leakage at 50Pa (Table 3).

CONCLUSION: EVALUATING AND INTEGRATING PERFORMANCE

The research undertaken in the studio demonstrates first that high performing curtain wall systems like that produced by Manko are indeed very high performing, and their actual performance is perhaps not fully appreciated by the green design community. Given the ability of these systems to reduce building infiltration and prevent the unanticipated thermal failures of improvised opaque wall systems, these systems will continue to be useful systems in low-energy buildings.

That said, the three systems introduced in this paper all showed performance advantages over the base curtain wall systems. It should be emphasized as well that compared to typical curtain wall systems, rather than the high performing system from Manko, the margins of improvement would greatly increase. And while economics was not a part of the studios’ analysis of experimental systems, it is probably that any of these three systems could be manufactured without greatly increased expense. It is also not out of the realm of possibility that any of these three systems could be proposed for a large project whose owner would support additional costs of development, and could be easily realized through direct collaboration between manufacturer, architect, and consultants.

A final conclusion can be made in related the studio to practice. In addressing the issue of performance in both a quantitative and qualitative manner, the students needed to embrace a more expansive body of ‘base knowledge’ about building physics as well as a science-based approach to experimentation. Performance outcomes needed to be objective, verifiable, relevant, and related to the comprehensive needs of real life projects. Knowing how to analyze designs was not simply enough – students needed to interpret the results. In summary of this point, the students needed to engage a deeper knowledge of building performance. Yet on the other hand, it was important for the students to maintain their design faculties during the work and not abandon the effort to work creatively and critically. This was important while the students were balancing multivalent performance problems in each experimental system, where energy efficiency was intersecting with architectural concerns of durability, comfort, quality of the environment, and overall sustainability. During this effort, the prototypes served as important models – “design models” in the tradition of the design studio – where both the problem and solution could be interrogated at the same time. In summary the studio was engaging building physics at a deep level while also integrating experimental methods and design thinking in a fluid process. This process will continue with the same collaborating partners from Manko and architects from BNIM and PGAV into the Spring 2015 semester, with the students charged to integrate their experimental systems in a comprehensive design exercise.

Table 1: Thermal performance comparison

Comparison of Thermal Performance: THERM and WINDOW Simulations w/ NFRC Guidelines		
System	Window Assembly U-Value, Glass and Frame, Btu/h-ft2-F	Infill System U-Value, Btu/h-ft2-F
Mfr’s Base System	0.29	N/A
System A: Structural Spacer	0.128	N/A
System B: Composite Node	0.29	0.11 (node/frame intersections) 0.05 (maximum, center of cavities)
System C: Foam Composite	0.29	0.025

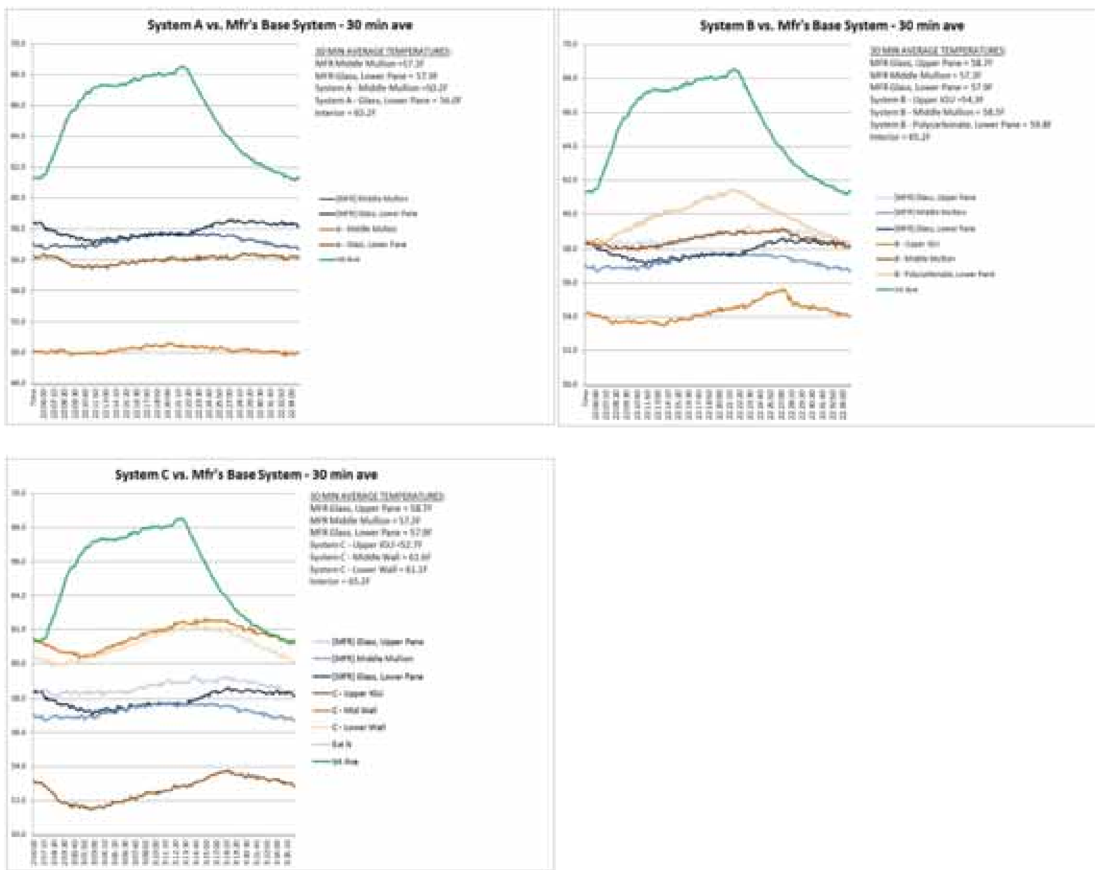

Figure 4: Temperature plots from prototyping testing. The temperature plots shown are from a 30 minute section from the larger 10-hour test. See table two for a comparison of average values and temperature differentials. Source: (Author 2014)

Table 2: 30-minute average temperature comparison

30-MINUTE AVERAGE TEMPERATURE COMPARISON			
	Measured Point	Surface T	$\Delta T = T_{int} - T_{surf}$
SYSTEM A	MFR middle mullion	57.3 °F	7.9 °F
	MFR glass, lower pan	57.9	7.3
	System A - middle mullion	50.2	15
	System A - Glass, lower pane	56	9.2
SYSTEM B	MFR Glass, Upper Pane	58.7	6.5
	MFR Middle Mullion	57.3	7.9
	MFR Glass, Lower Pane	57.9	7.3
	System B - Upper IGU	54.3	10.9
	System B - Middle Mullion	58.5	6.7
	System B - Polycarbonate, Lower Pane	59.8	5.4
SYSTEM C	MFR Glass, Upper Pane	58.7	6.5
	MFR Middle Mullion	57.3	7.9
	MFR Glass, Lower Pane	57.9	7.3
	System C - Upper IGU	52.7	12.5
	System C - Middle Wall	61.6	3.6
	System C - Lower Wall	61.1	4.1

Table 3: infiltration tests

INFILTRATION TESTS				
Configuration tested	Calculated @ 50 Pa	Calculated @ 75Pa	CFM per square feet* @ 50Pa	CFM per square feet* @ 75Pa
All systems masked - baseline	199.9	259.0	0.39	0.51
Mfr's Base System	0.1	0.9	0.01	0.06
System A: Structural Spacer	4.6	6.9	0.30	0.45
System B: Composite Node	2.6	4.3	0.17	0.28
System C: Foam Composite	0.0	2.1	0.0	0.13

*The area of each system tested for infiltration was 15.47 square feet. The total surface area of the test enclosure, minus the area of the systems, was approximately 512 square feet.

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ENDNOTES

1. The test enclosure was constructed using Bosch Rexroth aluminum structural components and enclosed using 3.5" Raycore SIP panels with polyurethane insulating cores. With an additional 0.75in of continuous insulation the envelope was increased to a thermal resistance of R 28.3 ft^2 °F hr/Btu. Interfaces between structure and envelope panels used gaskets that were compressed as panels were bolted together. All gaps were taped and any accessible gaps were filled with loose foam and backer rod. Prototypes installed over steel sill flashing and were separated by a block 2" of extruded polystyrene or 0.75" of expanded polystyrene, and all gaps were sealed with backer rod and silicon caulk.

2. Data collected during thermal tests referenced ASTM C1046-95 (2013) and ASTM C1155-95 (2013) but because of limitations, could not follow this standard entirely for calculating heat flux. Thermocouples were adhered to surfaces using aluminium tape spray-painted either black or white to eliminate effects of radiant heat loss on local temperatures. Data acquisition devices recorded synchronized data from all channels on a laptop computer at 5-second intervals. Individual thermocouples were calibrated using ice point calibration. Heat flux sensors were not available to the group, so individual temperature readings were used as an analogue for heat flux. This is possible because heat flow from conduction is equal to that of convection and radiation at these points ($q_k = q_C + q_R$). Radiation is negligible because of the nearly equivalent temperatures of environment and test surface and the reflective, foil-faced surfaces of the SIPs that reduce radiant heat transmission. Thus individual temperature readings indicate mostly heat transfer by convection ($q_C=h_c*A*\Delta T$), and given that all test points experience nearly the same heat transfer coefficient (h_c), we can regard the temperature differential (ΔT) as representing magnitudes of heat transfer per area (flux) among test points. For example, a 50% increase in ΔT suggests a 50% increase in heat flux.

3. Infiltration tests referenced ASTM E783-02 (2010). Following this standard, 'extraneous' gaps around each prototype were masked using masking tape to ensure only internal air leakage (around IGUs and in between frame connections) were measured. When a prototype was being tested, the other five prototypes were covered with 5 mil polyethylene sheet, taped to the exterior of the glass units. Data was recorded after the polyethylene sheet was 'sucked' to the surface of the other prototypes, indicating complete negative pressure was achieved inside the test enclosure. Testing used a duct testing apparatus joined directly to the the test enclosure, and tests were conducted at 50 Pa and 75 Pa and used an average of three 120-second averaged recorded by the testing instrument.