skylight
skylight
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Enclos can provide complete turnkey solutions to your most challenging facade requirements, regardless of size, complexity, product or building program considerations. We are highly experienced in the varied special conditions involving commercial construction, ranging from design through site installation, and including both BIM and LEED qualifications.
Glass in overhead applications brings special opportunities and equally special considerations. Among its predominant exterior wall applications, Enclos has produced a great many novel, fully-glazed overhead structures: skylights and glass roofs. The focus has been on expressive structural systems and long span applications. The opportunity to flood interior spaces with natural light not only enlivens the enclosed space, but the increased daylight levels can lead to significant reductions in energy consumption from artificial lighting and the reduction of the accompanying heating loads.

The solar heat gain resulting from a large horizontal glass exposure can easily offset any gain in energy efficiency from daylighting, however. It is important to understand and explore the active and passive tools at the designers disposal to balance the often conflicting attributes of natural light and solar heat gain. Passive design considerations include siting and orientation of the glass structure, as well as other factors related to the solar geometry of the skylight or glass roof design. Interior or exterior louver and shading systems can be incorporated into the design to reduce glare and direct solar penetration at key times of the day.

Glass technology presents another set of variables to consider. Glass makeup can be a powerful ally in the control of unwanted solar heat gain. Thin-film glass coatings, such as the now ubiquitous low-e coatings, can improve the thermal performance of glass quite significantly. Glass body tints, PVB interlayers, and ceramic frits applied to a glass surface can all be used separately in combination to fine tune glass performance to a specific application. Building integrated photovoltaic systems and other emerging technology hold the promise of turning building skins into energy producers — facade system power plants. Smart materials and control systems can integrate the skylight or glass roof with other building systems. Enclos can assist in the effective analysis of these many variables with respect to any specific application.

The backbone of any custom skylight or glass roof system, however, will be the structural system developed to support the facade enclosure, and that is the focus of this document. We have included select examples of the many projects we have been involved with over the years involving the use of glass in overhead applications, glass constructs with a unique and singular attribute: skylight.
Introduction to Enclos Technology

Enclos is expert in the design, engineering, fabrication, assembly and erection of custom curtainwall systems and structural glass facades, providing complete design/build services to the construction marketplace.

We specialize in innovative architecture and challenging building projects. No project is too large, no building site too difficult for our seasoned operations teams. Our work experience includes many projects with specialized materials, complex geometry, and innovative structural and mechanical system designs. Enclos curtainwall and facade systems incorporate state-of-the-art materials and performance.

The attributes most appreciated by our clients however are our site management capabilities and our track record of meeting demanding project schedules.

The integration of glass and structure is a predominant attribute of this expressive building form, often employed to maximize transparency in large public spaces. Enclos has played a leadership role in the development and application of this cutting-edge technology, including a range of structure types:

- cable nets
- cable trusses
- long-span truss systems
- grid shells
- spaceframes
- all-glass structures

Our glazing systems include point-fixed types in both bolted and clamped versions, as well as framed system types, all custom designed in response to specific project requirements. For more information see the section titled, Structural Glass Facades and Enclosures.

Managing the project delivery process is the core strength of Enclos, something at which we excel beyond all our competition. This capability provides us consistent control over the vital requirements of schedule, quality and cost, and allows us to consistently deliver top quality economically and on time. This capability is the basis for our many long term relationships with developers, general contractors and architects.

Each new project undertaken by Enclos is treated as unique, and a custom delivery strategy is developed in direct response to the singular set of considerations presented by the project. This custom strategy however, is developed through a uniform process unique to Enclos that embraces the spectrum of activities from preconstruction through design, engineering, procurement, fabrication, assembly, and erection. This process, developed and refined through the successful completion of hundreds of remarkably diverse facade and curtainwall installations, serves to mitigate the inherent risk of a challenging building project by enhancing the predictability of performance, schedule and cost.
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Design and Engineering

The foundation of a successful facade or curtainwall project is innovative system design and engineering. Our D&E group develops custom solutions to each new project, derived from a robust framework of Enclos technology and know-how. Design considerations range from the aesthetic and performance requirements determined in collaboration with the architect, to the fabrication and installation requirements that must be anticipated by the system design to assure a successful project completion.

An in-house team of engineers, architects and designers over 100 strong comprise the Design and Engineering Group at Enclos Corp, representing a unique talent pool that has consistently delivered innovative, effective and elegant solutions to the most demanding building facade requirements. Autocad, Inventor, Revit, Space Gass, Strand 7, FloVENT CFD, are among the many tools that comprise our design development process. Building Information Modeling (BIM) is another service we provide our clients.

Project Management

Project management is an empowered function at Enclos Corp, and key to our success. Personnel skilled and experienced in project management are vital to the success of any construction project. Our project management teams lead design development, production engineering, fabrication and assembly, and field operations, bridging these various activities to form an organized, unified continuum of project development throughout the design and build process. Enclos project management personnel receive extensive training and years of on-the-job experience before being appointed to the position and entrusted with the responsibility of running their own projects.

Our people understand the critical importance to a building project of on-time, on-budget performance, a fact which our past clients can best attest to. We will happily provide you with such references.
Curtainwall fabrication and assembly is a critically important part of the project development process. Enclos Corp maintains dedicated manufacturing operations in key geographic locations capable of providing fabrication services for the most complex designs and the most challenging project schedules. Our facilities incorporate state-of-the-art equipment and processes for curtainwall unit fabrication and assembly. In addition, to provide adequate capacity for the fluctuating demands typical of the building marketplace, we have developed a network of outside fabrication sources, all of whom have been rigorously trained and qualified in all aspects of Enclos systems materials, fabrication and assembly, and all of whom have successfully provided services on prior Enclos projects.

Design or material supply problems surfacing in manufacturing are a frustrating and costly annoyance; design or manufacturing problems surfacing on the building site are a disaster. There is far too much at stake in the building process to settle for anything less than top quality and the programs that consistently deliver it. Effective quality programs garner the participation of everyone in the organization from top to bottom while reaching throughout the web of company operations and activities. We have developed and refined our quality assurance and quality control programs over the span of many years and hundreds of diverse project experiences, another way that our deep experience works for you. These programs are robust and all embracing, ranging from management systems and procedures to the minutia of in-line quality verification processes. In addition, we develop a specific quality plan for each new project based on an analysis that identifies and accounts for any unique aspect of the project whether it be material type, location, site condition, performance requirement or design detail.

Enclos has been awarded many of its projects over its competitors because of its reputation for performance on the building site.

Everyone involved in the construction process knows the critical importance of the building site, the playing-field for the contracting teams. This is where the myriad complexities of a construction project converge and coalesce into architecture. The building site must be a particular focus for systems such as the building skin where a large part of the process takes place off site; design, engineering, fabrication and assembly all precede the delivery of material to the site and the commencement of field installation. Yet the site is where all must come together. These preceding activities must be accomplished with a keen eye to the site, anticipating unique site-specific requirements and developing effective installation strategy to assure an efficient and effective performance.

Field operations are a core strength of Enclos Corp, and the attribute for which we are most widely recognized by the building community.
A new facade technology has emerged over the past three decades driven by the pursuit of transparency in architecture among leading international building designers.

This new technology has evolved primarily in long-span applications of approximately 20 feet and over, and can be categorized by the various structural systems employed as support. New glazing systems are also a part of this emergent technology, with the various point-fixed systems finding most frequent use.

Recognizing the importance of structural glass facade technology, Enclos took action to acquire the technology and expertise required to play a leadership role in implementing and further developing this innovative technology in the US marketplace. As a result, we are now providing complete in-house services for both the curtainwall and structural glass facade areas of the building skin, all as a single-source package backed by the deep technical and financial resources of a national specialty contractor.

Characteristics of structural glass facade technology include: highly crafted and exposed structural systems with long-spanning capacity, integration of structure and form, simultaneous dematerialization and celebration of structure, complex geometries, extensive use of tensile elements, specialized materials and processes, an integration of structure and cladding system, and a complex array of design variables ranging from facade transparency to thermal performance and bomb blast considerations.

Frei Otto developed and popularized cable nets as a structural system in the 1960s and 70s. Architect Helmut Jahn with engineering firm Schlaich Bergermann applied the technology in a most innovative manner as a flat cable net supported glass facade for the Kempinski Hotel in Munich, circa 1992, fueling widespread interest in this structural form in glass facade applications.

Cable nets represent the ultimate in elegant minimalist structural systems and can provide optimum transparency when the effect of a sheer glass membrane is desired. The glass is supported by a net geometry of pre-tensioned cables. Designs can be flat, or the net can be pulled into double-curvature. A clamping component locks the cables together at their vertices and fixes the glass to the net. Large pre-stress loads in the net structures require the early involvement of the facade design/build team with the building engineer.

Another minimalist structural system is that of cable trusses. While cable trusses can vary widely in both truss design and configuration with vertical, overhead, vaulted and domed forms easily achieved, the trusses themselves are most often characterized by spreader strut elements representing the only compression members in the structural system. As with cable nets, these systems rely on the pre-tensioning of truss elements to provide stability, and thus benefit significantly from the early involvement of the facade design/build team.
Grid Shell structural systems are another means to minimize the visual mass of structure. Configurations can be vaulted, domed and double-curved. Systems can be welded, bolt-up, or some combination of each. Grid shell structures with integrated cable bracing can produce a highly efficient structure with a refined aesthetic. Cable pre-tensioning may be required on such systems. Grid shells can be used in vertical and overhead applications, as well as to form complete building enclosures.

This is the earliest form of structural glass facade dating back to the 1950s and the French Hahn system used at the Maison de la Radio in Paris in 1953. Here 2-story glass plates were suspended and laterally stiffened by the use of glass fins set perpendicular to the plates at the vertical joints between them. This technology was popularized by the Willis Faber & Dumas Building, Ipswich, England circa 1972. In this curving facade designed by Foster Associates, multiple plates of reflective glass are suspended to provide one of the first examples of an entire building facade in frameless glass. This project inspired a diffusion of glass fin technology in numerous applications throughout Europe and America starting in the 1970s and continuing today. Glass fin-supported facades still represent one of the most transparent forms of structural glass facades and an economical solution especially at lower spans.

Enclos provides custom fin-supported facade designs for any application.

Glass facades are comprised of a glass system supported by some form of structural system (except glass fin-supported walls in which the glass is hung and braced laterally with fins). As the pursuit of transparency is a frequent reason for the use of structural glass facade technology, point-fixed (frameless) glass systems are most often integrated into the facade design. These can be systems where the glass is perforated and bolted or non-perforated and clamped. Such systems typically provide optimum transparency and design elegance. However, the structural systems employed in structural glass facades can easily be designed to accommodate any type of glass system. In some applications framed systems can provide certain practical or economical advantage.

Enclos is capable of developing and providing any type of custom glazing system for structural glass facade applications.
In addition to the glass and structural systems that comprise structural glass facade technology are the components that in turn comprise these systems, components quite unlike those typically used in exterior wall systems. The use of tensile elements in the form of steel cables and rods is a primary design strategy to dematerialize the structure and enhance the transparency of a facade design. Compression elements are frequently minimized or eliminated, and where present are crafted from cast and machined components in an elegant expression of exposed structure. The fittings and components that tie these structural members together are similarly crafted. An entirely different set of material and process considerations come into play.

The Enclos design team has mastered these materials and processes as a necessary prerequisite to their appropriate application in component design. We can develop and provide custom designs of remarkable diversity in response to your particular project needs. Where appropriate, we can also source off-the-shelf components from a variety of suppliers, all carefully qualified to Enclos Corp standards and subject to our uncompromising quality assurance program. All this, from concept design through installation, as part of a single-source package from the largest national specialist in structural glass facade technology.

Bridge builder and engineer John A. Roebling first manufactured wire rope in America in the 1840’s. These materials ultimately found their way into the vernacular of architecture through such stunning works as Mathew Nowicki’s Dorton Arena of 1952 and the Ingalls Rink at Yale University of 1958 designed by Eero Saarinen. Structural glass facade technology has embraced these tensile materials as a means to minimize the structural profile of the support system. Wire rope composition, material type, finish, and end terminations are all important considerations in specifying these materials, which are available from a relatively limited number of manufacturers and specialty fabricators. Enclos Corp has put many of these manufacturers through its rigorous qualification process, resulting in several exceptional vendor/partners that have successfully provided materials on various structural glass facade projects that we have completed in recent years.
The use of steel rods as a substitute for cable in the design of structural glass facades was a practice borrowed from the yacht racing industry, and popularized in the Louvre Pyramid designed by IM Pei. The rods are most commonly fabricated from ASTM A316 stainless steel because of the material’s combination of strength and corrosion resistance. In high load applications or when super thin profiles are desired, there are other higher strength stainless options. The rod terminations are often custom designed and can be quite refined, with the intent of minimizing or eliminating any exposed threads, turnbuckle or other tensioning mechanism. Rod fabrication typically involves slipping the end fittings over the rod and upsetting the rod ends through a process called cold-heading. Alternately, equally elegant threaded fittings have also been developed. Depending upon the design of the structure, cable systems can have significant advantages over rod systems, particularly with respect to cost. However, some feel that the refined appearance of a rod system is worth a premium cost.

Casting is an ancient process with a longtime role in the construction industry, including the naming of a “cast-iron architecture” during the industrial revolution resulting from a dramatic increase in the availability of low cost cast materials. Castings were much later used to spectacular affect in the gerberettes and other components for the Center Pompidou by architects Rogers and Piano. The casting of structural components however, demands a high level expertise in both the design and fabrication process. Cast nodes for the space frame structure on the Javits Convention Center in New York were famously discovered during construction to contain cracks, requiring the disassembly of nearly half the structure and a project delay of nearly two years. While most of the castings utilized in structural glass facades are glass-fixing components of stainless steel, such as the “spider” fittings that attaché point-fixed glass to the supporting structure, many options exist in both material and process depending upon the component size, design and application.

In many respects, structural glass facade technology is more closely akin to the automotive industry than it is to conventional construction. Spider fittings are about as far from the brick as a building component can be. Structural glass facades are highly engineered structures built to very high tolerances. There is also an important visual aspect to the components because of their use in exposed structural systems. Despite a widespread pursuit of facade transparency, many designers choose to express this exposed structure in dramatic fashion, sometimes even at the expense of ultimate transparency. These factors and considerations make the use of machined components a frequent and effective choice. We design custom components or specify off-the-shelf parts as appropriate, and source both from our network of vendor/partners.
Enclos Corp is known for providing technically superior exterior wall systems at competitive prices, and in fact this is one of our core commitments to our clients. We achieve this through a progressive ongoing program of research and development. This program has resulted in continuous refinements to our core systems, as well as yielding new system designs with improved performance attributes. The bulk of the current R&D program falls within the following categories:

Security design and blast-resistant facade technology is a particular expertise of Enclos, demonstrated by a portfolio of completed projects meeting the most demanding security requirements, including many federal courthouse projects. Security Design remains an ongoing focus of our R&D program.

Our security and blast-resistant technology is discussed in the pages immediately following.

Rising energy costs and the energy performance of the nation’s buildings have become predominant concerns. While the thermal performance of a curtainwall building skin is primarily dictated by the thermal properties of the glass makeup or panel cladding material, Enclos has focused its R&D effort on the performance of the framing system to both determine behavior and identify opportunities for improvement. The result has been thermal enhancements to existing systems as well as the development of premium systems with improved thermal performance.

In addition, our project work includes innovative dual-skin facades and cavity wall systems featuring the state-of-the-art in energy performance. We have in-house mechanical engineering capability and computational fluid dynamic analytical technology to assist in the design of these advanced wall and enclosure systems.
We have recently crossed an important threshold in the evolution of civilization. For the first time in history, the majority of earth’s people reside within our urban cities. This is reflected in the increasing density of these urban areas and evidenced by the many residential tower projects which have sprung up in cities around the world. Along with the increasing density has come escalating noise pollution. These factors have combined to produce a growing concern among developers, architects and building occupants regarding the acoustical performance of urban habitats.

In recognition of this, Enclos launched an R&D initiative intended to identify the key variables in the acoustical performance of its facade and curtainwall systems. The program involved testing inter-story as well as outside-to-inside acoustical behavior, and has resulted in refinements to basic systems as well as new premium curtainwall framing systems with superior acoustical performance.

Enclos facade and curtainwall systems are of known and proven performance, having been tried and tested in numerous mockups and hundreds of custom building applications over many years. They have consistently conformed to required specifications for water penetration and air infiltration, as well as other demanding specification requirements. However, increasing urban density, rising fuel costs, and concerns over rapid climate change are resulting in escalating demands on the performance of the building skin. Anticipating this trend, Enclos has been hard at work developing new facade and curtainwall systems with improved behavior in all key areas of performance. We are confident that we can and will continue to provide technically superior systems at competitive prices.

Testing is a key component of any R&D program. Testing activities as part of the Enclos program have involved explosive testing on blast-resistant designs, structural testing to hurricane wind loads, acoustical and thermal testing, and many others. In addition, most of our custom curtainwall designs for particular building projects require some program of mockup testing, and we have performed many dozens of such tests over the years.

Enclos Corp has its own dedicated in-house test facility augmented by several major certified testing facilities across the nation. The later facilities are used when special capabilities are needed and independent confirmation of performance is a requirement.
51 Louisiana
Washington, DC

owner Dweck Properties
architect Rogers Stirk Harbour + Partners / HKS
gc Clark Construction Group
facade consultant Curtainwall Design Consulting
completion 2009
program 10-story glass enclosed atrium
building type office
facade design/build program for entire atrium enclosure
description a 10-story glass enclosed atrium with exposed structure creates a dramatic public space and ties 2 adjacent office buildings together

51 Louisiana and 300 New Jersey Avenue is a state-of-the-art office building project in Washington, D.C., located just one block from the U.S. Capitol. The project includes the construction of a new glass-enclosed office building that will serve as an extension of two existing office buildings, all connected by the new centerpiece atrium.

Enclos was responsible for the challenging facade program that encloses the new 10-story atrium space. A yellow tree-like steel construct provides the atrium structure, supports a trapezoidal flying roof of glass, and carries exposed HVAC and other building system components. Multiple levels of skybridges tie the complex together. As all structure and systems are exposed, the highest level of craftsmanship was required for every aspect of the project. The project is the first office building by London-based Rogers Stirk Harbour + Partners and Pritzker Prize winning Principal Richard Rogers.
LEED Silver certification is expected for the project, and its sustainable features include a green roof and treatment of water from the atrium in the existing building’s storm-water processing system.

1. The vertical wall is 90’ tall by 40’ wide
2. Stainless steel tension rods tie back to primary structure to stabilize the wall structure
3, 4. The yellow truss supports the skylight roof
The wall that forms the entry to the new complex climbs vertically over 90 feet and then slopes back nearly 14 feet to join the glass roof. The entire wall is hung from above, with a series of suspended horizontal trusses providing the minimal structure. Point fixings tie the glass to the trusses at the end of 2-foot truss armatures. Spring connections at the base and sides of the wall accommodate movement under design loading.

The skylight is a low ridge and furrow design covering 12,500 square feet in plan area. The glass module is approximately 4 feet by 12 feet and incorporates a full perimeter supported insulated-laminated glass panel with a ceramic frit and low-e coating.

The glass enclosure actually ties together three separate buildings of different construction and constructed during different time periods when building practices and code requirements varied. The result is considerably different movement behavior between...
them during design loading. Of course, even identical buildings will not move in phase when subject to identical loading conditions. The Enclos team built a 3-D digital model of the glass enclosure and surrounding buildings as a tool for studying the relative building movement. The intent was to develop a design for the roof and wall that could fully accommodate these movements with an efficient and minimal structure. A high level of transparency combined with a minimal but expressive structure was particularly important in the design of the glass wall.

Rather than designing to limit movement, the structure is designed to accommodate it. Spring mechanisms were designed into the structural system that allows the structure to absorb relatively high deflections and relative building movement without inducing high compressive stresses into the structural components. A network of stainless steel rods are used to stabilize the top of the wall.
Clark Construction, with 40 subcontractors and an average of 200 site workers each day, constructed the project over a 3-year period. Space was very limited on the dense urban site, and office buildings immediately adjacent to the site were operational throughout construction. An Enclos project management and site operations team worked closely with Clark and other subcontractors to assure optimum site logistics and minimal disruption to nearby building occupants.

Key to the success of the complex installation of the glass enclosure was a system for the glass wall and skylight that embraced the requirements for installation in its varied design. The skylight roof system, for example, was constructed in fully glazed subassemblies off-site. The skylight system was designed with a split-beam structural element running in the primary spanning direction. Ladder frames were assembled under factory-controlled conditions into 12-foot wide sections up to 48 feet in length. The finished sections were stacked on flatbed semi-trailers and shipped to the site on a just-in-time basis to minimize site inventory and storage space. The sections were lifted from the trailer by an overhead crane and set and bolted into position. Crane setting positions were carefully mapped and their availability coordinated with the other trades.

The off-site concentration of the assembly work and detailed installation logistics planning improved product quality, speeded assembly and installation, and minimized disruption to this challenging building site.
1. trough skylight detail
2. ridge skylight detail
3. skylight detail with wall bracing rods
4. skylight plan with crane lift mapping
5. wall detail at portal frame
6. wall detail at edge
7. spring at portal frame
8. detail drawing of spring at entry portal frame
developer  Second Street Holdings LLC, Louis Dreyfus Property Group Inc
architect  Kevin Roche John Dinkeloo & Associates
gc Tompkins Builders
completion  2004
program lobby wall: 90 feet high and 60 feet wide; skylight: 55 feet long and 60 feet wide
building type  government
structure  double curve anticlastic cable net made of 20 mm cables clamped via stainless steel cast nodes. Supported by the perimeter concrete structure and an intermediate steel delta truss
glass  face glass—Viracon, 1 1/4 inch total thickness, five-foot by five-foot panel size insulating glass consists of 1/4 inch heat-strengthened clear glass with low-emissivity coating on the second surface, a shading coefficient of 0.43, winter U-value of 0.48 and summer U-value of 0.55; 1/2 inch air space and silver spacer bar; inner panel consists of 1/2 inch laminated glass consisting of 3/16 inch clear heat-strengthened glass, 1/16 inch polyvinyl butyl and 1/4 inch clear heat strengthened glass.
skylight— 15/16 inch total thickness consisting of: 1/4 inch clear tempered glass with low-e coating on the second surface, a shading coefficient of 0.33, a winter U-value of 0.29 and a summer U-value of 0.29; ceramic frit on the second surface, with Viracon Pattern 5005 and frit color V912-LF (white); 1/2 inch air space and silver spacer bar; 1/2 inch laminated glass consisting of 1/4 inch clear tempered glass, 1/16 inch PVB and 1/4 inch clear tempered glass for the inner panels.

Glass-clad cable-net structures are fast evolving in the United States as one of the dominant forms of high-transparency facade technology.

The lobby area of SEC is enclosed with a cable-net supported 60-by-90-foot glass wall and a 60-by-60-foot skylight. The combined surface area is approximately 9,000 square feet. The structure comprises 28-millimeter stainless steel cables and clamp fittings or nodes. A 60-foot-long double curved triangular truss spans the two concrete super columns at the top of the wall and provides support at the intersection of the wall and skylight. The truss also acts as a load transfer and stabilizing element for the adjacent building towers. The wall net comprises 15 rows of horizontal cables and 12 rows of vertical cables and the skylight net comprises 12 longitudinal and 10 transverse cables. The vertical cables of the net wall align with the longitudinal cables of the skylight.
The vertical and horizontal cables are clamped at their intersections with custom stainless steel node assemblies, which in turn receive the hardware by which the glass is fixed to the net. The slight radius the wall structure follows in plan provides the curvature in the horizontal direction. Opposing curvature in the vertical direction is provided by embedded cable connections within the concrete super columns. The opposing curvatures give the cable net its saddle shaped surface and stability.

In practice, cable-net structures are remarkably resilient and forgiving as they are designed to move. They can deform many times the deflection criteria of conventional steel or aluminum structures without permanent deformation or failure. Deflections in the flat nets can equal 2 feet under wind load in a 100 foot span. Contrary to being a problem, this allows them the flexibility to best withstand the extraordinary loadings resulting from seismic events or bomb blasts. As with all emergent building technology, cable nets number among the highest priced facades in the marketplace, due largely to development costs. However, the systems are relatively material-efficient and very simple, and market pricing drops rapidly. In efficiently designed structures, with the dissemination of assembly and installation know-how, look for cable-net technology to become competitive in price, resulting in widespread application.
Enclos has developed various glass systems for application on its cable net designs, including point-fixed drilled and non-drilled systems and panelized systems. For the SEC net, Enclos has developed an innovative unitized glass-framing system that can be bolted directly to a modified cable-net node assembly. The system avoids the premium cost associated with point-fixed glass systems and allows for competitive domestic glass supply.

The anticlastic geometry will result in a major mitigation in the deflection of the cable nets. However, this feature results in a warped surface that cannot be easily clad with the planar glass.

Double curved glass is expansive and impractical for insulated glass and cold bends have limitation on the glass size and the preload warpage.
In this project Enclos first optimized the cable-net geometry to achieve minimum distortion while maintaining enough curvature to control the skylight and wall deflections.

The result is a hybrid geometry extracted from the surface of a torus.

The remaining warp is then concealed in the interstitial space of the thin aluminum frame.

Installation Sequence
In order to achieve the proper shape in the double-curved nets, the clamps must be accurately positioned on the net, and the tensioning of the net must be accomplished with all cables, vertical and horizontal, simultaneously. This requires rigorous methodology frequently involving sophisticated hydraulic jacking gear. Enclos utilizes special survey techniques to map the position of each node. Compensating adjustments in the tensioning of the net can then be computed and implemented. The trick, then, with the cable-net structures is in the tension: first, determining appropriate theoretical cable pre-tensions with respect to boundary conditions, so as to yield the most efficient shape of the net. The following Sequence was used at SEC:

1. assemble the net the factory and attach cables and nodes in a horizontal position allowing compensation for final tensioning
2. pretention the net using perimeter hydraulic jacks attached to a temporary space frame with similar stiffness as the actual structure
3. adjust the nodes to their final position using accurate laser measurements and clamp the node with the required torque values
4. wrap the cables and nodes in plastic covering and de-tension the net and roll the net around a spool
5. transport the spool to the to the site
6. erect the supporting structure including the delta truss and assemble the perimeter jacking system at the support locations
7. drape the net and attach to the perimeter jacking system and the delta truss
8. tension the net to the final position utilizing all of the jacks simultaneously and check node locations; install glass
Performance yields form

Developing the geometry for a curved cable net structure is much a part of the art of this technology. The geometry for a project like SEC is a critical issue, as cable net behavior is extremely sensitive to relatively minor changes in boundary support locations and pre-tension forces. The final shape of the net must be determined as a function of performance.

The goal is to control deflections, optimize stress distribution, and minimize pre-tension requirements and resulting reaction loads to the boundary structures. Subtle adjustments in the shape of the net can significantly decrease required cable pre-tensions as well as the forces in the cables under load. In addition, a coordinated manipulation of the net geometry can consolidate the variation in glass panel sizes required to glaze the net.

Without this design coordination it is possible that a different size may be required for each grid panel of the net. This will significantly increase cost both with respect to the glass itself as well as with its handling and installation. Poor net geometry can also result in unnecessarily excessive warping in the glass cladding, as discussed previously.

The unique geometry developed for the SEC project provided two significant advantages: it eliminated any permanent warp in the individual glass panels, and it allowed for each row of glass to be repeated rather than each panel being a different size and shape.

Strength of Geometry

Form-finding

The first step in the design of double curve cable nets is the process of finding the equilibrium position of the net under pretension forces. The pretension geometry is a function of a number of parameters, including the boundary condition profiles, maximum reaction allowed at these boundaries, the maximum allowable deflection during service loads, and the cladding constraints imposed by the planar nature of the glass.

The general approach initiates by assigning an initial approximate shape for the geometry which assigns the grid size and the boundary curves. Usually this initial shape is flat. Then a pretension force or force density (force / unit length) is assigned to the cables. Then the an iterative nonlinear approach is used to converge to the final position.

If the assigned force in the two directions is specified to be the same and constant the resulting geometry is a minimum surface.

In-service analysis

Upon completion of the form finding the super imposed loads are applied to the cable net. The vector loads are applied at the nodal points and the net deflections and cable forces are computed.

Because cable movements are relatively large, the applied loads cannot be assumed to remain in the same point of application. Further more it is possible that some cable elements will be relaxed (void of any tension) in certain load combinations. These constraints require a non-linear approach to the solution of analysis incorporating both the geometrical and material effects.

The main factor in controlling the forces and deflections of the cable nets is the sag ratio. The curve following shows the sensitivity of the peak deflection in as a function of sag ratio (prescribed boundary curvature / boundary length).
Effect of sag ratio (ratio of prescribed boundary curvature to the boundary span) on the deflection of double curve cable wall and maximum cable forces.

Wall deflection as a function of wind speed for conventional glass walls, flat cable nets and double curve cable nets.
owner City of San Jose
architect Richard Meier & Partners Architects
gc Turner Construction Company / Devcon Construction
facade consultant Curtainwall Design Consulting
completion 2005
program 18-story tower, freestanding 10-story dome-capped rotunda, 100 ft dome; 550,000 sqft total
building type civic
facade design/assist and design/build program included cable truss system with point-fixed glass for rotunda and dome at 21,000 sqft; tower facade is custom metal and glass unitized curtainwall system with louvers, sunshades and operable windows
dome structure comprised of 12 bays, each 26 feet wide spanning between AESS structural steel arched beams rising to a height of 108 feet; exterior stainless steel cable truss system spanning between arched steel beams, with stainless steel spreaders as sole compression element
glass point-fixed system with custom spider to provide adequate movement to accommodate requirements of California Building Code; rotunda glass is point-fixed and perforated at the corners, tempered and laminated, with a high performance low-e coating; large panels required in the barrel area approximately 10 feet high by 6 feet wide, comprised of 3/8-.060-3/8 inch glass and laminate; smaller dome panels are 3/8-.060-1/4 inch; rotunda glass imported from specialty Spanish glass fabricator Cricursa
Richard Meier & Partners Architects is well known for uncompromisingly modernist designs: formal and monumental with light-filled spaces, and sweeping expanses of metal, stone and glass. Enclos has collaborated with Meier on many past projects, including the sprawling Getty Center art complex in Los Angeles. The San Jose Civic Center includes a slim 18-story metal and glass tower housing City Hall, a 3-story council wing, and features an adjacent public plaza dominated by a free-standing dome topping a 10-story glass rotunda.

At 100 feet, the rotunda's diameter surpasses that of the U.S. Capitol building, and it is virtually all glass. The transparency and openness are intended to reflect the democratic form of government in which the United States prides itself.

Enclos Corp provided pre-bid services to the architect. Michael Palladino, partner with Richard Meier and lead architect on the San Jose project, laid out the program for the dome. The dome capped rotunda heralded an old tradition of such building form in public buildings, but he wanted to combine this aspect with the use of state-of-the-art technology, “beyond any skylight ever built.” Palladino wanted to “take the next step in dome design” with a highly transparent all glass structure, using a filigree tension based support system. The decision was made to bid the tower curtainwall and the rotunda as a single design/build facade package.

With Enclos providing design-assist services, a concept was represented in the architect’s drawings and a performance testing extensive mockup testing of dome glass system: including seismic, water and air infiltration installation strategy cable truss system required pre-tensioning to forces ranging up to 22,000 lbs; a detailed installation method statement was developed to facilitate assembly and installation; hydraulic equipment was used to achieve prestress forces
San Jose Civic Center

 specification was included in the project tender documents. Enclos was ultimately the successful tender for curtainwall contractor.

Curved glass is used in the lower barrel of the rotunda, with simple curvature required in one direction only. Compound curved glass to provide true curvature to the dome surface was considered, but ultimately rejected for budgetary reasons, so the dome surface is faceted with flat panel shapes hung from the cable trusses. The rotunda enclosure is unusual in its use of an exterior structural system to support the glass. Stainless steel cable trusses span horizontally between structural steel columns in the rotunda and the arched beams that form the dome. The sole compression elements in the system are the stainless steel spreaders that, along with approximately 2.5 miles of stainless steel cable, comprise the trusses. Spider-type fittings attach to the inside end of the spreaders, providing the point fixings that secure the glass.

Arguably the most challenging design aspect of this project was accommodating the large inelastic building drifts required by the new California Building Code in areas of high seismic activity. Conventional point-fixed systems can be inadequate in these applications, thus Enclos developed a new system involving a custom spider design capable of providing for large in-plane movement. The system allows for up to 3 inches of in-plane movement at each fixing. A custom spider component was required to accommodate this movement. Enclos developed a custom spider that is investment cast of a special heat-treated stainless steel alloy with mechanical properties well beyond the 316 stainless alloy typical to conventional spider fittings.

An extensive testing and mockup program was undertaken for the spiders and dome structure. Additional information is available upon request.
1 Exploded view of the skylight dome
2 Diagram of typical cable truss
3,4 Inelastic seismic movement of the spider during mockup testing
5 Glass movement during a seismic event
Casting Process for Spider Fittings

The investment casting process is a complex, multi-step process. The basic steps are illustrated here.
1 Wax injection
Wax replicas of the desired castings are produced by injection molding. These replicas are called patterns.

2 Assembly
The patterns are attached to a central wax stick, called a sprue, to form a casting cluster or assembly.

3 Shell building
The shell is built by immersing the assembly in a liquid ceramic slurry and then into a bed of extremely fine sand. Up to eight layers may be applied in this manner.

4 Dewax
Once the ceramic is dry, the wax is melted out, creating a negative impression of the assembly within the shell.

5 Casting
In the conventional process, the shell is filled with molten metal by gravity pouring. As the metal cools, the parts and gates, sprue and pouring cup become one solid casting.

6 Cut-off
The parts are cut away from the central sprue using a high speed friction saw.

7 Knockout
When the metal has cooled and solidified, the ceramic shell is broken off by vibration or water blasting.

8 Finished castings
After minor finishing operations, the metal castings—identical to the original wax patterns—are complete.
Shure Corporate Headquarters
Chicago

owner CenterPoint Properties
architect Murphy/Jahn
engineer Peller & Associates
gc Harbour Contractors, Inc.
completion 2000
program 7-story; 65,000 sqft
building type office
facade design/build program including custom vaulted glass roof and glass fin wall of over 30,000 sqft; interior glass elevator enclosure, handrail, stairs, wash basins, ceilings
glass exterior low-iron insulated laminated with custom frit for roof glass, insulated glass with low-e coating for glass fin walls, laminated glass fins, all glass point-fixed non-perforated, supplied by Eckelt; interior glass low-iron tempered monolithic
description this building rises like a jewel box above its neighbors in a Chicago suburb
In granting an AIA Design Excellence Award (Chicago, 2005), jurors agreed that this building is at the leading edge of design and technology, in the best Chicago tradition. The seven-story box is overlaid with triangular screens that form loggias to the street and serve as projection screens for the company’s logo. The exterior wall is a single-shell, insulating glass facade between the slab edges. Concrete ceilings are exposed, with mechanical systems placed beneath raised floors. The interior is organized around a full-height atrium with three glass elevators and topped by an innovative glass roof. At the top two levels the atrium connects to a two-story light-flooded showroom for the company’s products.

1 View of glass roof and handrails, with glass elevator core and wall beyond.
2 Glass roof at intersection of vertical fin wall.
3 Retainer plates hold the 7’ x 5’ glass panels at four locations along the perimeter.
4 Section drawing showing roof truss design.
5 A four-way armature at the cross section of cable trusses and glass fins supports the glass panels.
Shure Corporate Headquarters
Chicago

Design/build and engineer-of-record services were provided for a portion of the project, including a highly innovative glass roof and glass fin walls totaling over 30,000 square feet. Custom roof trusses were fabricated and rigged in factory, then installed on the roof using a rolling gantry. The roof structural system incorporates a laminated glass beam element and intermittent cable trusses to lighten the structural profile. Roof cladding glass is insulated laminated panels with an offset ceramic frit on two interior surfaces. The Enclos design team developed an innovative point-fixing system utilizing a “pinch-plate” or clamping spider assembly that eliminated the need for drilling holes in the glass, thus providing considerable savings to the project. Low-iron glass was used throughout to further enhance transparency.

Laminated glass fins provide wind load resistance to the vertical facades, and integrate the primary entry portals into the building. A major component of the scope on this project was interior design that included floor, ceiling and handrail glass. The cores for the glass elevators are enclosed in glass surrounds, and even the elegant fritted glass counter tops in the lavatories were provided as part of a comprehensive design/build program.
Brain Power vs Crane Power

The building site is a primary cost center in all building projects. Advanced facade technology concentrates labor in the factory, providing higher quality and lower cost. The prefabricated and pre-finished systems must still be assembled and erected on the building site. This fundamental activity must be anticipated and designed for during facade design development.

One of the more significant site costs is typically the equipment expense associated with the use of a crane to lift components into place. The crane and operator costs can be significant on facade projects with constrained site conditions, which is frequently the case. The rectangular plan of this glass skylight lent itself to an installation method facilitated by a simple gantry crane mounted on rails parallel to the longitudinal axis of the skylight.

The gantry was designed along with the skylight roof and fabricated by the truss fabricator. Instead of a large crane through out the installation process, a small crane was required for only a few days to lift the gantry and materials to the roof, and to remove the gantry on completion the installation. This strategy provided significant savings to the owner and made possible the accommodation of an accelerated delivery schedule.

1 Exploded rendering of componentized spider assembly.
2 Finite element solid modeling was used to perform stress analysis of the armatures supporting the glass panels.
3 Vertical facade with glass fin support.
4 Glass fins can be used to support skylights also.
5 A custom gantry was designed and fabricated to facilitate erection.
6 Roof glass installation in process.
7 Illustrations from the Crystal Palace, 1851 by Joseph Paxton: a source of inspiration for the installation of the glass roof.
Orlando International Airport: Airside 2

developer Greater Orlando Aviation Authority
architect HOK
structural engineer Walter P. Moore
gc Clark Construction Group
completion 2000
program 3-storys; 305,000 sqft
building type airport
facade a centralized glass skylight and custom glass fin wall create a highly transparent hub
glass insulated, point fixed
description three dramatic tension truss skylight systems act as the focal point of Florida’s busiest airport

The HOK aviation design team wanted to modernize an existing hub design strategy for the new Airside 2 Terminal at Orlando International Airport. A conventional heavy steel truss backer structure supporting boxy aluminum framed skylights and curtain wall systems was to be avoided. Modifications to the building shell involved the application of cutting edge design and building technology.

At the hub itself, lightweight stainless steel cable trusses support 3 elliptical long-span skylights. The skylight system utilizes an integrated cladding strategy comprised of insulated, point-supported glass with stainless steel fittings and hardware that tie directly into the compression members of the cable trusses.

The Airport General Tram enclosure makes use of the ASI Vanderbilt LS system, the long span version of this elegant and highly economical glass wall structural system comprised of steel tension trusses and integrated glazing system. In this custom application the trusses were curved to provide a radius section to the glass wall enclosure.

There is lightness to the resulting enclosure enhanced by the effect of transparency achieved with the tension based structural systems, and the systems detail and use of material are complimentary to the contextual aeronautical context.
technology. The architect’s design goals were thus achieved. However, the advantages of advanced building technology do not end with the aesthetic; the building team provided the owner with extended warranties covering the long-term performance of the enclosure systems and materials.

1 skylight plan
2 skylight showing cable trusses spanning between perimeter fabricated steel trusses
3 glass fin spanning between cable trusses
4,5 hydraulic jacking system for tensioning cable trusses
6 glass fin and spider attachment detail
7 typical glass truss drawing
The Lloyd D. George Federal District Courthouse is the home for the district court in Las Vegas, and was the first federal building built to comply with post-Oklahoma City blast-resistance requirements. Following the events of the Oklahoma City Bombing in 1995 and the attacks upon the World Trade Center in 2001, the federal government mandated an increase in building structure security measures that have since become industry standards.

The innovative systems developed by Enclos for this project were the first in the country to be subjected to full-scale testing to verify performance under blast loading. All systems surpassed the newly created blast security criteria.

The 450,000 square foot L-shaped facility incorporates a complex facade program. Ceiling heights of 22 feet required long-spanning cladding materials. Precast wall panels measuring 22 feet by 10 feet clad much of the exterior. A dramatic steel and aluminum canopy projecting from the top of the building shadows the plaza, where a three-story rotunda serves as the public lobby.

A 60-foot diameter cable truss supported glass dome caps the rotunda, also provided by Enclos in compliance with challenging bomb-blast requirements. The walls facing the plaza are of glass curtainwall inset into precast frames with an integrated louvered sunscreen.
Advanced structural silicone and laminated glass were combined in inventive ways to meet the blast requirements. Testing took place at the Department of Defense's Large Blast Thermal Simulator in White Sands, New Mexico.

Results showed that in the event of an explosion the curtain wall panels would maintain fundamental integrity and act to mitigate the risk of injury in the event of an attack.

Weidlinger Associates conducted the blast engineering.
Seven custom beam elements float in a sea of tension, suspended and stabilized in a net of stainless steel tension elements. The tension structure is clad with laminated point-fixed glass creating an effective transparency of gem quality. Upon entering the foyer of the New Helen and Martin Kimmel Center for University Life at NYU, visitors are greeted by an unusual tensegrity structure creating the entrance enclosure. The vaulted enclosure reaches an extraordinary level of transparency and dematerialization with the primary roof beams seemingly floating in mid air. The canopy structure required pre-stressing of the cables to achieve its structural integrity.

Facing Washington Square Park at Greenwich Village, the Kimmel Center includes a 1,000 seat theater, the largest performing arts facility south of 42nd Street, and a 600 seat auditorium. Student club lounges, conference and catering hall, music practice space and offices complete the building program.
1 The tensegrity structure forms the entry enclosure to the university.
2-4 Point-fixed laminated glass attaches to spider fittings on the glass beams.
5 Stainless steel anchors for the cable assemblies during installation.
6 Cable and beam assemblies during prestressing operations.
7 Typical cable truss section.
8 Integration of load transfer plate at beam end.
9 Glass attachment detail at outside and inside corner of cable truss.
Davis Brody Bond was designing a 22-story luxury residential building located in Manhattan’s Upper East Side neighborhood. The intent was to convey a contemporary, elegant image yet compliment its more traditional neighbor, and the building’s design featured a canopy that was entirely unconventional yet very sophisticated.

At the entrance, — so thin and clean that passerbys might not even give it a second glance — is a glass canopy that cantilevers approximately 20 feet from a steep pipe in the rear. What makes this 10-foot wide canopy entirely unique is its lack of steel structure. Instead, the glass beams act as the structural support carrying most of the load.

ASI acted as the design/builder for this unique but state of the art structure.

1. the canopy cantilevers 20 ft from the building with no metal support
2. connection detail of glass beam leafs
3. the entire structure was test assembled off-site
Metropolitan Museum of Arts
Manhattan

owner City of New York
architect Kevin Roche John Dinkeloo and Associates
completion 2006
building type cultural
description A two story atrium with glass enclosed skylight is the centerpiece for the museum’s Greek and Roman displays

The Leon Levy and Shelby White Court yard doubles the height of the Greek and Roman Galleries by adding a two-story structure with historically themed columns and glass skylight roof. A three phase renovation doubled facility space to 60,000 square feet for exhibitions. The Met Museum now has on permanent display over 90% of their ancient Greek and Roman collection — half of which had previously been in storage — bringing their active display total to more than 35,000 pieces dating back as far as 312 A.D.

The architectural expansion feature is a custom vaulted skylight with a unique and minimal structure design. The skylight floods the museum exhibition space with natural lighting. The primary structure is a series of rolled steel arches fabricated to AESS standards. A secondary aluminum system spans along and between the arches to support the glass. The aluminum system incorporates and integrated gutter. The system features concealed bolted connections. Glass panels are insulated-laminated with a low-e coating.
Deloitte Building
Costa Mesa

developer Segerstrom
architect Murphy / Jahn
gc Matt Construction
completion 1997
program 15,000 sqft skylight
building type commercial
facade a centralized glass skylight and custom glass wall create a highly transparent entrance
glass insulated, low-e coating, 70% ceramic frit, point-fixed
description three dramatic tension truss skylight systems act as the focal point of the building entrance

1 Vault structure with two lenticular super cables running along the width of the vault to resist lateral loads and a series of king post trusses across the vault to carry the vertical loads
2 Entrance at base of vault reveals system transparency.
3 Cable truss system encloses vault sides.
4-6 Glass attachment, footing, and cable connection details.
7 Isometric view of the vaulted structure and shade wings.
8 Vault and side wall intersection.
These adjacent structures in Costa Mesa were developed during the 1970’s, originally as the Imperial Bank Tower. A late 1990’s renovation included tying the structures together by utilizing state-of-the-art facade technologies to modernize the buildings. The new glass lobby connects the tower with the neighboring building to the south, providing entrances from the east and west. The overhead and vertical glazed surfaces on the vaulted structure are 70% opaque fritted glass with low-e coating, producing a highly transparent building skin capable of mitigating solar heat gain.

The lobby enclosure is 120 feet (36.6m) by 32.5 feet (9.9m) in plan, and located between a multiple story tower to the north and a single story building to the south. Glass panels are supported by structural steel beams and cable trusses. Perforations in the glass accommodate a bolted connection capable of up to 5 degrees rotation relative to glass plane.

Glass fixing is accomplished with a stainless steel spider component providing up to 0.3 inches (8mm) per glass joint shear deflection under wind or seismic loading. Glass panels are tempered and laminated, and sealed with a butt-glazed silicone joint between the panels. The roof glass has a dark frit pattern with low-e properties. Glass complies with the intent of UBC 1994 chapter 24, “Glass and Glazing”. Single panel deflection is limited to span/50.
Marriott Canopy Manhattan

owner Marriott International
architect Perkins Eastman Architects
completion 2000
program canopy entrance to a 35-story early 20th century tower
building type hospitality
facade design/build custom steel and glass cable-supported canopy

The challenge of implementing a modern entrance canopy on an older building was to balance the historical charm of the original 1920s facade with the contemporary aesthetic desired by the architect and owner. The minimalist canopy design was developed as a study in contrast, the ultramodern steel and glass against the arched neoclassical masonry forms of the existing facade, to provide a striking and distinctive entranceway to the 35-story tower at Lexington Avenue. The hotel recently completed a $24 million renovation, and the new canopy welcomes guests to the Marriott’s 629 rooms and 17 suites. The hotel hosts a variety of NYC events in its 21,000 square foot event space.
convenient because of its close proximity to Central Park, Rockefeller Center, Broadway theaters and 5th Avenue’s retail district. The hotel is readily accessible from Grand Central and Penn Stations, the subway, and NYC’s three major aviation hubs.

The inspiration for the canopy derived from the remarkable iron and glass canopies of late 19th Century Paris. Enclos designers worked closely with the architect to develop a concept that would meet the aesthetic and pragmatic goals of this project. The primary structure is a fabricated and painted steel frame with a novel support system of upper and lower stainless steel catenary cables that tie back to the existing building structure. The suspended frame supports a glass “shell” that is comprised of laminated glass panels that appear to float between the Corinthian columns of the existing building. Suspended beam elements incorporate a glass fin at their outboard tip in a finger-nail like fashion to further minimize the structural profile.

The steel structure was fabricated and test assembled off-site to assure fit-up in the field, where a narrow window for canopy installation allowed no room for error. Custom stainless steel cable and fittings were used throughout. The tempered and laminated glass panels are tied to the structure by stainless steel point fixings. Architectural lighting is supported from the structure and used to dramatic effect during the evening hours.

Interfacing a new cable-supported structure with an existing building with a masonry facade is an art form rooted in fine craftsmanship. The installation of the structure required scaffolding over the entire sidewalk and entrance area to the hotel to create a work platform for the Enclos installation crew. Penetrations were carefully cut through the masonry facade to reach to steel structure concealed within. Anchor assemblies were designed to facilitate quick and easy assembly of the structural components. The canopy was ultimately completed on schedule and with only minimal disruption to hotel operations.
The Glass Umbrella canopy is a small experimental art project. It is comprised of 17 unique glass panels cascading over an exterior stairway in a small office building, accessible only through a locked interior door. It is prominently visible from the exterior of the building, and intended as a feature element of the architecture. The path to implementation of this innovative structure traversed a landscape of questions: how to design, fabricate and install something never attempted before, and how to define, describe, quantify, analyze, mold, laminate, cut, transport and install.

The 17 panels were mapped and modeled per the architect’s specifications. Stress analysis revealed the distribution of forces through each panel and verified adequacy. A molding technique was conceptualized and steel molds designed to facilitate the slumping process. Unavoidable inaccuracies in the slumping process created the requirement for a clamping device capable of a wide range of adjustability.
Bending the Rules

By all accounts, the Glass Umbrella marks the first time large sheets of float glass have been subject to such extreme curvature. (Frank Gehry used similar but less extreme bent glass in a vertical orientation on the interior of the Conde Naste project, in the same approximate timeframe.) However, to regard the project as high-tech, as in the application of cutting-edge technology, would be a gross misunderstanding of the story of the Glass Umbrella, which, like many such innovative architectural designs, is much more a tale of high-craft than high-tech.

Prior to our involvement, the designers identified an interested fabricator, a local family-owned second generation operation specializing in glass bending. They were introduced to us as a possible fabrication source and displayed both an understanding of the glass requirements and optimism that the panels could indeed be fabricated. Their initial concern was with the molds, as each of the 17 required a unique mold of complex geometry. We developed an egg crate approach that allowed us to map a section curve of the glass surface and translate that into a drawing that could easily be flame cut from steel plate. Plates fabricated from the incremental x and y sections were simply slotted together and tack welded to create a stable mold base with the required surface. 17 unique molds were constructed in this manner. The glass was to be heated and slumped over these molds.

Glass slumping is not a high tolerance process, especially when attempting deep, double-curved surfaces. Even in the plastic state glass remains relatively stiff. Single curvature bends are easy. The double-curvature forms act to further stiffen the glass locally as a function of the geometry, and the material resists slumping in certain areas. It was impossible to predict the exact deformations attainable through this slumping process. It was thus impossible to predict the exact footprint or edge profile resulting in the slumped panels. For this reason, the glass was initially cut oversized, slumped, laminated, and finally the edges were trimmed to get as close as possible to the desired footprint.

In the slumping process, the mold surface was covered with fiberglass blankets. Two identical oversized pieces of glass were then balanced upon the mold surfaces, one atop the other. The molds were rolled into the furnace, the doors closed, and the furnace fired, generating a temperature that carried the glass through the transition zone and into the plastic state.

Parameters based upon empirical experimentation were developed, allowing us to approximate the magnitude of possible slumping. When these were overlaid against the required shapes, many areas were identified where the curvature exceeded these parameters, especially with the 3/8 inch composite glass panels. The architect was quite insistent upon attaining the curvatures as originally designed with the hair blower. We thus made extraordinary efforts to achieve these curvatures as closely as possible, experimenting with variables of temperature and time, and whatever technique we could
identify that might improve the process. In many instances this required extreme measures, including pushing on the hot glass with long rods inserted through small openings in the furnace sides in an attempt to force it into conformance with the mold surface. The next step in the process was laminating. Glass laminating technology derived from research conducted by the glass industry in the 1930’s with the primary intent of providing a safer product for automotive glass. Decades of development have resulted in a laminating technology for architectural glass that finds extensive use in the building arts today. The most typical practice involves the use of polyvinyl butyral (PVB) in thin sheet form. The PVB is sandwiched between panes of glass, and the composite panel subjected to heat and pressure, bonding the PVB to the adjacent glass surfaces. The process requires approximately 4 hours at 280°F (138°C) within an autoclave to provide the required pressure and facilitate the bond. The primary advantages of laminated glass involve the redundancy provided by the composite panel comprised of multiple glass ply, and include safety and security. When one glass ply of a laminated panel breaks, the panel remains intact. Most laminated glass is 2-ply, however multiple ply are possible and are finding increasing application in structural applications, as in stair treads, landings, and even stringers, as well as beam and column components. Laminated glass also provides enhanced performance in extreme loading events, such as
blast and high-impact loads. Laminates intended for extreme loading applications will sometimes include an inner ply of polycarbonate. In addition, laminated glass is an effective sound dampening material and is finding increasing application for its acoustic properties. An important consideration for the Glass Umbrella project was that the glass panels could be trimmed to their final profile as a final fabrication step, something not possible with heat-treated glass.

As with the slumping process, never before had the lamination of such dramatically shaped glass been attempted. The slumping process sometimes resulted in differences between the two pieces of glass laid atop the mold in the areas of the most extreme curvature. If the dif-
slumping marking

ferences were great enough they would result in a bubble in the laminate where the PVB was unable to bridge the gap between the panels and would adhere only to one side. Lesser differences simply resulted in some magnitude of residual stresses as discussed above.

trimming and edge treatment

If a panel made it this far without bubbles or breaking, it was time to trim the piece to provide the desired edge-profile. Our designers devised a technique for transferring the perimeter profile to the undulating glass surface. The surfaces were then scored on both sides and broken away to reveal the new edge. Another area of experimentation was with the edge treatment. Cut glass edges are usually treated to provide safety in handling the glass, as the raw cut edges are extremely sharp. The treatment is usually some form of grinding process, whether done on a CNC machine or by hand. In our case it was by hand; even if we had access to a CNC type machine it could never have accommodated the wild edge geometries of the Umbrella panels. The
The fixing of the glass panels turned out to be very near as challenging as the making of the panels themselves. As seventy-three panels were made to provide the final 17, so were 3 variations of the fixing system prototyped before arriving at a workable solution. There were several problematic conditions to be accommodated by the fixing system. There was a small overlap between the panels, with an upper panel shingling its lower neighbor. The fixing system somehow had to bridge from the structural support below, through, or around the glass panel immediately above,
and to the adjacent panel atop the first, while providing for the exceedingly large variations in entry angles due to the poor tolerances of the slumped glass.

Much of our work is rooted in the study of natural form. Here, an articulated arm was conceived to reach from the steel pipe support and cradle the panel edges, rather like the palm support of a hand with fingers folding around the edge and over the top to restrain the glass from uplift. It was a complex problem requiring many design iterations. We learned from hard experience the critical requirement of mockups when developing such a unique system. The first two mockups were great successes in demonstrating to us just how to assure the breaking of the glass panels, how easy it was to break them by inducing just small local moment forces into the area of support. These mockups informed the development of a design that provided full rotation at the connection point, minimizing or eliminating any moment transfer into the glass. But by this time we had broken a number of panels and accumulated quite a number of stainless steel plate components of various
configurations, all destined for the scrap heap and a recycled future.

*Installation*

Glass installation is most often facilitated by suction cups attached to some type of crane as discussed above. We had a small crane at the site for this purpose, but as in the factory, the suction cups would not serve. Instead, our riggers had to devise a byzantine cat’s cradle of nylon straps that would hold the glass in something near to its installed position in the structure, as the panels were too heavy to manhandle in place. Each piece of glass had to be treated differently, finding its unique point of balance, providing enough support so as not to overstress the glass locally. Most of the panels had to be held in position by the crane until the clamps could be fixed.
Enclos Press
Publications

Inter-Story Acoustical Evaluation of Unitized Curtainwall Systems - 2008

Analysis and Design of Spandrel and Shadowbox Panels in Unitized Curtain Walls - 2009

Enclos: Collective Works - 2009

Facade TecNotes Series:

1 Skylight

2 Double Skin

3 Architecturally Exposed Structural Steel (AESS)

4 Airports

5 Healthcare

6 BIM and the Building Facade

7 Cable Nets

8 Security

9 LEED Skins