# Skin and Bones: Structural System Choices for Long Span Glass Facades

MIC PATTERSON
University of Southern California
G.G.SCHIERLE
University of Southern California
MARC E. SCHILER
University of Southern California
DOUGLAS NOBLE
University of Southern California

## INTRODUCTION

The building skin is a vitally important architectural consideration. No other building system combines as significant an impact to both a building's performance and aesthetic. The use of glass as a component of the building envelop has been increasing since its initial introduction as a building material, accelerating in the twentieth century owing to the development of high-rise steel framing systems and curtain wall cladding techniques. Little has changed in the core technology of glass curtain walls over the years. Much has changed in the building arts in the past decade alone, however, in terms of aesthetic and performance drivers, as well as in available structural systems and materials.

In response to these market forces, new glass facade types have emerged in spot applications over the past two decades. These new façade designs play off the primary attribute of glass, its transparency. As a body, a case can be made that these completed works represent a new façade technology. Characteristics of this technology include; a dematerialization of structure combined with highly crafted and exposed structural systems, integration of structure and form, complex geometries, extensive use of tensile elements, specialized materials and processes, integration of structural and cladding system, and a complex array of design variables ranging from facade transparency to thermal performance and bomb blast considerations.

The push by leading architects for transparency in the building envelope has been the primary driver in the development of the new façade types. The façade structural systems have developed in parallel with the development and application of frameless, or point-fixed glazing systems. While any type of glazing system can be supported by the new façade structures, the point-fixed systems are the most used. Structural system designs with minimized component profiles were desired to further enhance the transparency of the façade. This quickly led to structural designs making extensive use of tensile structural materials as rod or cable elements.

This emergent façade technology has been evolving for over twenty years, with considerably varied application in the commercial building marketplace. Public sector works include airports, courthouses, convention centers, civic centers, and museums. Private sector work includes corporate headquarter buildings, hotels, retail and mixed-use centers, churches, institutes and other privately funded public buildings.

While applications have been limited to a small niche market in the overall construction industry, many innovative designs have been introduced over the years, with many more imitations and variations springing from those. As a result, this technology has matured over the years and is no longer largely comprised of experimental structures. It has been tried and tested in a considerable diversity of built form; structural systems have been adapted to façade applications; specifications and methods have been developed, tested and disseminated; practitioners have built dozens of highly innovative façade structures in a variety of applications; development costs have been absorbed. An infrastructure of material suppliers, fabricators and erectors has developed in support of increasing project opportunities. These factors have combined to make the technology more accessible and competitive. Thus, this body of façade types represents a mature and robust building technology positioned for broader application in the marketplace.

At the same time, owing to the high-profile success of recent projects featuring advanced façade designs, increasing numbers of architects are interested in incorporating this technology into their projects. The new façade designs are becoming increasingly valued by the design community for both their varied aesthetic and the ability to provide a controlled transparency ranging from very high to modulated in response to environmental considerations. Growing interest and a maturing technology promises significant growth in the small niche market for advanced façade technology. There exists the potential for a partial conversion in the larger curtain wall market, whereby the advanced technology replaces conventional curtain wall in an increasing number of applications.

These glass façade types have evolved primarily in long span applications of approximately 8 meters and over, and can be categorized by the various structural systems employed as support. While these facade structure types are derived from the broad arena of structural form, they have become differentiated in their application as facades. Building designers need information, delivery strategies, and tools to facilitate the incorporation of this advanced façade technology in their designs. Knowledge of the fundamental considerations of material type, grid module, component sizing, spanning capacity, span/depth ratio, deflection criteria, finish options and relative costs is a prerequisite to the effective deployment of the technology in any specific design application. The intent of this paper is to discuss some relevant attributes of two categories of these structural system types; truss and cable systems, along with a brief discussion of the role of strongbacks in relation to these systems. Glass system options will also be briefly discussed.

## FAÇADE STRUCTURE TYPES

Façade technology is complex, glass facades even more so, with long-span glass facades topping the challenge. Appropriate designs are as unique to the particular requirements of any architectural project as is the ultimate form of the building. The designer must balance myriad variables to develop an optimum solution to the façade requirements.

Central to the application technology is the development of a supporting structure. An interesting diversity of structure types has evolved in these façade applications, with each of the types possessing varying attributes that may impact their appropriateness to a specific application. A cable net may provide optimum transparency in a given application, but a steel truss system will likely prove to be more flexible in accommodating other design considerations that might be addressed with such elements as shade systems, louvers, canopies, screens, or light-shelves, features that can be integrated into the design of and supported by the truss elements with relative ease.

## STRONGBACK

Strongbacks are the simplest form of support for a glass façade, but are only useful in relatively short spans. They can be comprised of simple steel or aluminum open or closed sections with provisions for the attachment of the glazing system. Rectangular tubes are often used, and provide a useful flat surface for the attachment of veneer glazing systems. Round pipe or tube sections see frequent application, with integral weldments to accommodate glazing system attachment. Extruded aluminum sections can be quite complex, and designed to facilitate the attachment of an integrated glazing system. They are commonly used in curtain wall systems where the floor-to-floor span is in the 3 to 4 meter range. Aluminum is more expensive than steel, however, and does not possess the superior mechanical properties of steel. Thus, in structural applications with spans over 6 to 8 meters, steel is generally the material of choice.

Strongback sections can also be built up of multiple standard steel sections, such as two tubes or pipes joined by continuous, or more likely discontinuous web plates welded between the two sections. This strategy can effectively increase the spanning capacity and efficiency of the Strongback.

The relevance of the strongback is as a supporting component in a façade system intended to provide uniform glazing over varied spanning conditions. Some designs might use a conventional curtain wall system in typical areas and a structural glass system on an exposed long-span structure, presenting a design challenge at the interface. Other designs call for a uniform glazing condition throughout. In such a case, a short span, medium span, and long span solution may be required. The strongback provides the solution for the short spanning condition. A simple example is a long spanning truss with a square or rectangular outer chord, presenting a flat face for the attachment of a veneer glazing system. If the same or similar square or rectangular section is used for the strongback, the glazing system can be applied seamlessly across the varied spanning conditions.

## PLANAR TRUSSES AND TRUSS SYSTEMS

Planar trusses of various types and configurations can be used to support glass facades. The most common application is a single truss design used as a vertical element with the depth of the truss perpendicular to the glass plane (fig.1). The trusses are positioned at some regular interval, frequently a gridline of the building or some uniform subdivision thereof. The truss spacing must be carefully determined as a function of the glass grid. The individual trusses comprise a truss system, the structural system supporting a structural glass façade. A truss system can include more than one truss type. Primary trusses for example, may be separated by one or more cable trusses to heighten the system transparency. The truss systems often incorporate a minimal tensile lateral system, bracing the spreaders of the cable trusses as well as the primary truss elements against lateral buckling. Alternatively, lighter trusses may span horizontally between widely spaced primary vertical trusses, providing lateral support and attachment for the glazing system.

An effective strategy as discussed earlier is to employ a square or rectangular tube as the outer chord of the truss (fig.1). The same section can then be utilized as a horizontal purlin element spanning between the trusses at the glazing grid. A bolted connection can be detailed along the truss chord to accommodate the attachment of the purlins. The resulting truss system provides a high tolerance exterior grid of flat steel matching the glazing grid. The steel grid can then accommodate the attachment of a simple, non-structural veneer glazing system, providing a high level of functional integration of the structural and glazing systems with favorable economy.

While most frequently vertical in elevation and linear in plan, façade truss systems can be sloped inward or outward, and follow a curved geometry in plan. Truss elements can also be manipulated to provide a faceted glazing plane.

Truss systems can incorporate other structural elements, as with the steel purlin discussed above. Glass fins, cables, other truss types, and conceivably even cable nets can be incorporated as elements within a façade truss system.

## SIMPLE TRUSS

Geometric configurations of simple truss types include variations of Pratt, Warren, and Lenticular trusses. Truss design is a function of the structural considerations of span, loading, pitch, spacing and materials. A deflection criterion for truss systems making predominant use of simple truss elements is typically in the range of L/175. [2] The application of trusses as part of a glass façade system brings other considerations; the glazing plane and grid will dictate certain geometric pa-

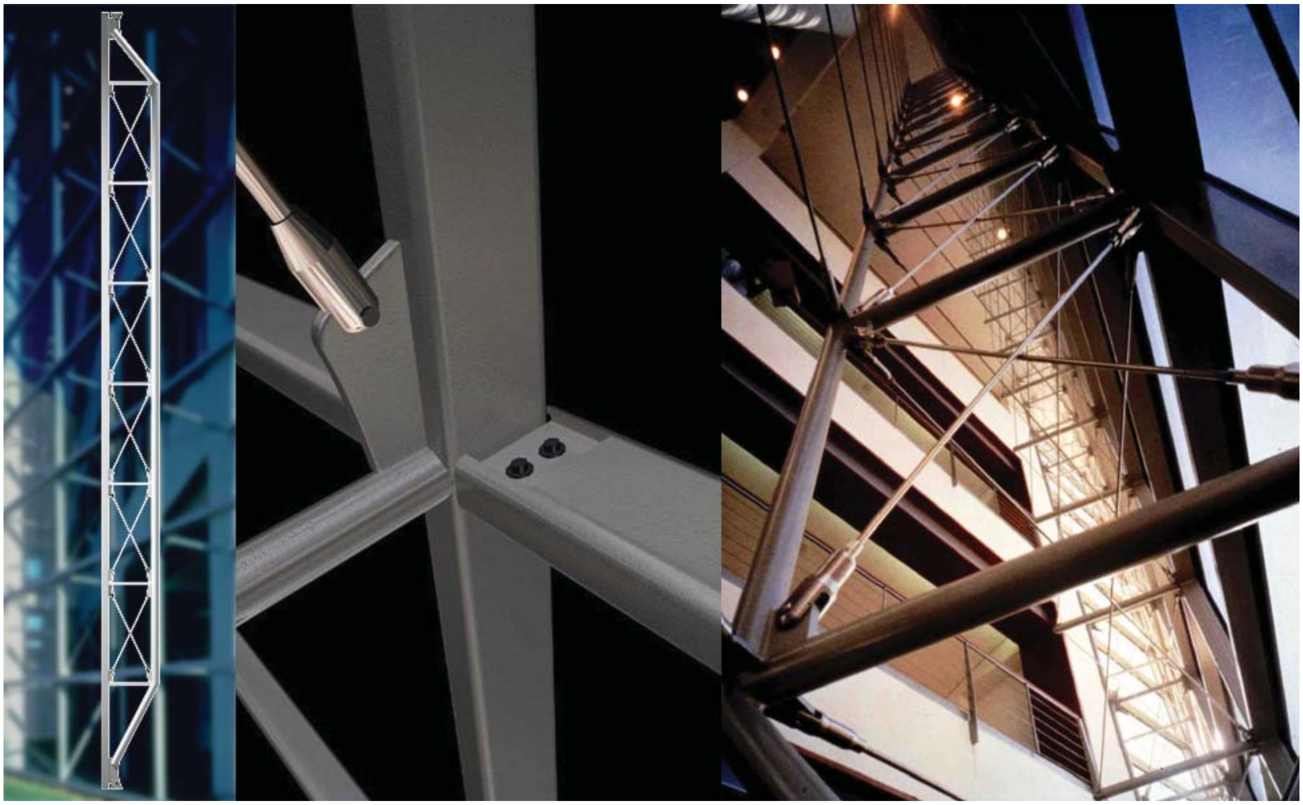

Fig.1: A simple truss system with tension rod bracing and a horizontal purlin mirroring the exterior glazing grid can provide relatively high transparency with considerable economy over more complex truss systems. Virtually any glass system can be adapted to this truss system.[1]

rameters of the truss system, deflection criteria must be considered, limitations in the design of boundary supports may eliminate certain system types, the intended glass system must be evaluated in terms of the supporting structural system. However, aesthetic considerations are always in play, and are often the primary design driver. Long-span façades make use of exposed structural systems. The emphasis has been on elegant structural system designs, highly crafted system components, and a general dematerialization of the structure in an effort to enhance overall system transparency.

The primary strategy in achieving this dematerialization involves the use of tension elements. Interestingly, this is consistent with a strategy of efficiency and sustainability; doing more with less material. The following steps[3] were initially recommended as a means to improve the economical efficiency of a truss, a technique here suggested for application to truss systems and the pursuit of transparency:

1. Minimize the length of compression members.
2. Minimize the number of compression members, even if the number of tension members must be increased.
3. Increase the depth of the truss as much as is practical; this will reduce the axial forces.
4. Explore the possibility of using more than one material in the truss, one for compression and another for tension.

A structural system designed such that certain elements see only axial tension forces allows for those elements to be significantly reduced in section area from elements designed to accommodate compression loads. A 100 millimeter diameter tube or pipe element can potentially become a 10mm rod or smaller, significantly reducing the element profile. The overall effect can be quite dramatic. There are several theoretical reasons for this, but the simplest is that buckling disappears as a phenomenon.

The tensile elements themselves are most frequently comprised of cable or rod materials, often in stainless steel, although occasionally galvanized and/or painted mild steel materials are used. End fittings can be quite sophisticated in design, intended to present a minimal profile and leave no exposed threads while still accommodating the requirements of assembly and tensioning. These are generally high tolerance machined components with a quality finish. High strength alloy steels can be used for rod materials to further reduce their profile. Cables are, as a rule, more economical than rods, sometimes dramatically so. Cables are capable of bending within a specified radius with no loss of structural capacity, and can thus be used as longer elements intermittently clamped but requiring only two end fittings. Bent rods are most often impractical, so rods must be provided as discrete linear elements of greater quantity, each requiring two end fittings. The additional quantity of end fittings drives up both the fabrication and assembly costs in most applications. Nonetheless, this method is sometimes used as an aesthetic preference. Both cable and rod fittings are currently available from a number of suppliers providing a wide variety of system types and aesthetics.

Steel fabrications in exposed structural façade systems are frequently specified per standards developed by the American Institute of Steel Construction (AISC) for the fabrication of Architecturally Exposed Structural Steel (AESS). This standard provides for the specification of such important considerations as surface finish of the steel and the finishing of welds. Welds can be specified as ground smooth, and even polished if circumstances warrant. Such care with the fabricated steel will lead to equivalent concerns with the finish of these materials. High performance two and three part aliphatic urethane coatings are available in a range of standard and metallic colors that provide excellent results, both with respect to performance and appearance. The procedure typically involves initial substrate preparation of cleaning and surface blasting followed by a zinc-rich prime coat prior to application of finish coats.

## GLASS SYSTEM OPTIONS

Truss systems provide great flexibility in accommodating the options in glazing system types. Descriptions of the most common of these follow.

Veneer or stick systems use minimal aluminum extrusions and generally require near continuous support as discussed earlier. While far from the optimum with respect to system transparency, they are relatively low in cost.

Panelized systems consist of glass panes assembled with framing elements to form a glazed panel. The frames possess structural properties allowing for interim support by the truss system while providing continuous support to the glass pane, thus minimizing deflections to the glass pane itself. The frames can provide two-sided or four-sided support, and can mechanically capture the glass pane or be structurally glued to the glass pane using appropriate silicone glazing materials. When environmental concerns dictate the use of insulated glass units, panelized systems can prove to be more economical solutions than point-fixed glass systems, with little of no loss to façade transparency.

Point-fixed glazing systems find most frequent use in structural glass façade systems. The glass panes are either bolted or clamped with components providing attachment to the truss system. The most common type is often referred to as a “spider” system. A four-armed fitting, usually of cast stainless steel, supports four glass panes at adjacent corners on the glazing grid and ties back to the truss system. The spider fitting is designed to provide for glazing system movement under environmental loading, as well as to accommodate specified field tolerance during assembly. A variety of spider systems are available from the suppliers of cable and rod rigging systems.

The above method of point-fixing has the disadvantage of requiring drilling and countersinking of the glass panes, and with insulated glass units the insertion of a sealing ring in the space between the glass panes around the bolt hole. Each insulated glass unit requires the drilling of at lease eight holes.

An alternate strategy that eliminates the need for drilling and instead clamps the glass at the perimeter is frequently referred to as a “pinch-plate” system. Here the spider fitting is rotated 45 degrees so that the spider arms are aligned with the glass seams. A narrow blade of metal penetrates from the spider through the center of and parallel to the glass joint. A relatively small clamp plate on the outside surface of the glazing plane is then fixed to the blade, clamping in place the two glass panels on either side of the seam.

In either case, field applied wet silicone in the gap between adjacent glass panes provides the weather seal. In contrast, conventional curtain wall systems typically utilize compression gaskets to provide the weather seal. The disadvantage of the field applied silicone is the requirement for expensive field labor, and potentially problematic site conditions (adhesion issues related to temperature, moisture and dirt). The advantage of this method is that leaks are seldom encountered, and if so are easily fixed.

## GUYED STRUT / MAST TRUSS

Guyed struts or mast trusses use tension elements to stabilize a central compression element (mast), usually a tube or pipe section. The cables attach at the mast ends and incrementally at the ends of "spreaders" struts of varied length attached at intervals along the length of the pipe. The spreaders get longer toward the longitudinal center of the mast, thus forming a cable arch between the mast ends. Two, three or four of these cable arches can be radially spaced about the mast, acting to increase the buckling capacity of the mast and allowing for the use of a smaller mast section.

A planar mast truss formed by two of these cable arches 180 degrees opposed can be used as a primary truss element in a structural glass façade (fig.2). The glass plane can be located in the plane of the masts, placing one of the cable arches on the inside and one on the outside. Alternately, the spreaders on one side can be extended out to form a plane parallel to but offset from the mast plane, thus enclosing the entire truss system within the façade envelope. In this configuration, a "dead load" cable is typically employed to support the dead load of the glass. The cable would be located at the top of the glass plane on a cantilevered outrigger and drop vertically behind the glass plane connecting to the extended spreaders at their ends. Some form of lateral bracing of the primary struts is usually required (a minimal horizontal cable serves this purpose in fig.2 bottom left).

A large cavity double-skin façade could be easily accommodated by this truss system, with glass planes at both ends of the spreaders, or at the mast plane and either end of the spreaders.

Fig.2: Monolithic glass panes are being attached to the spreaders of these mast trusses. A vertical dead-load cable supports the spreader struts just behind the glazing plane. In this case, horizontal glass will be installed at the top of the trusses back to the building roof.[4]

## CABLE TRUSS

Pursuing the truss development guidelines established earlier, the next step is to remove the big compression member, the mast, from the truss element described immediately preceding. This leaves the spreader struts as the sole compression elements in this truss type (fig.3). However, this has been accomplished at a price; the remaining truss is no longer stable, and cannot even stand on its own, much less carry any load. The solution is to tension the truss against an upper and lower boundary structure. This represents a fundamental change in truss behavior from those preceding. Cable trusses must be prestressed, or externally stabilized, to function as load-bearing structural elements. This type of truss, and truss systems comprised of this truss type, can be referred to as open systems. The preceding truss types were internally stabilized, or closed systems; stability was provided as a function of truss geometry, requiring no interaction from the boundary structure to provide intrinsic truss stability.

There are several important nuances in designing with open systems. Appropriate prestress forces required to stabilize the truss and control deflections under design loading conditions must be determined as part of the system design. These prestress forces must be balanced against the reaction loads that will be transferred to the boundary structure. The more deflections are limited, the higher the system prestress that will be required, and the higher the resulting reaction loading transferred to the boundary structure. An appropriate deflection criterion with these systems might be L/140 or more[2]. Perhaps the predominant consideration in the design of an open truss system is assuring that the boundary structure is designed to handle the reaction loads, and that the affect is factored into the budget early in the design process. It is important to note that the loads generated from the prestress requirements are not intermittent loads like wind or seismic loads, but continuous loads like dead loads.

The next challenge is to assure that the correct prestress forces are in fact achieved in the field during installation of the truss system. Long span systems can require prestress forces achievable only with hydraulic jacking systems, and must include connection detailing carefully developed to support the field pretensioning of the system.

What is gained is a significantly enhanced transparency to the façade system. While many cable truss geometries are conceivable, lenticular and inverted geometries with horizontal compression struts are most common. A spider or other fitting type can be positioned at the end of the extended

Fig.3: A series of inverted cable trusses define this glass façade. The spreader struts are the only compression elements in the system. Truss stability is achieved by prestressing the cables against the top and bottom boundary supports.[5]

spreader struts to fix the glass. More conventional panelized glazing systems can also be accommodated. Cable trusses can also be positioned horizontally between vertical mast trusses in a hierarchical scheme.

## CABLE SUPPORTED STRUCTURES

The next step in the move towards dematerialization of these truss systems is to delete the compression struts, thus yielding a new category of open system façade structure that is cable based instead of truss based. All that remains from the former cable truss category are the cable elements, which can be tensioned vertically against top and bottom boundary structure. If adequate prestress forces can be achieved, the cables can be used to support glass. Dual function clamping components that clamp first to the cables can then be used to clamp edges or corners of adjacent glass panes on the glazing grid (fig.4). The glass plane can be straight or curved in plan. A narrow glazing grid will result in a higher density of cable elements, thus lowering the prestress requirements for each individual cable. Nonetheless, high prestress forces will be required to control deflections. Deflection criterion of L/45 or L/50 is commonly used[2], producing a highly flexible system with significant deflections under wind load.

## CABLE NET

The addition of horizontal cables to the system described above yields a cable net, an open system capable of 2-way spanning behavior. Adding the horizontal cables to a *straight* plan geometry of vertical cables produces a flat cable net structure, with an orthogonal cable grid defined by the relative spacing of vertical and horizontal cables. The addition of the horizontal cables makes controlling system deflections easier, assuming an effective spanning distance, resulting in lessened prestress requirements in the cable elements. Simple flat cable nets as described here have been constructed with spans of 50 meters or more. One cable net of more complex, faceted geometry and using a hierarchy of cable sizes has been constructed in China that spans nearly 100 meters.

## DOUBLE CURVED CABLE NETS

The addition of horizontal cables to the system of vertical cables aligned to a *curve* in plan, as described in Cable Supported Structures above, produces another kind of cable net. If the horizontal cables are aligned to a curve in elevation opposing curvature of the vertical cables in plan, the horizontal and vertical cables can be tensioned against each other to form a double-curved (anticlastic) surface with unique properties (fig.5). The oppos-

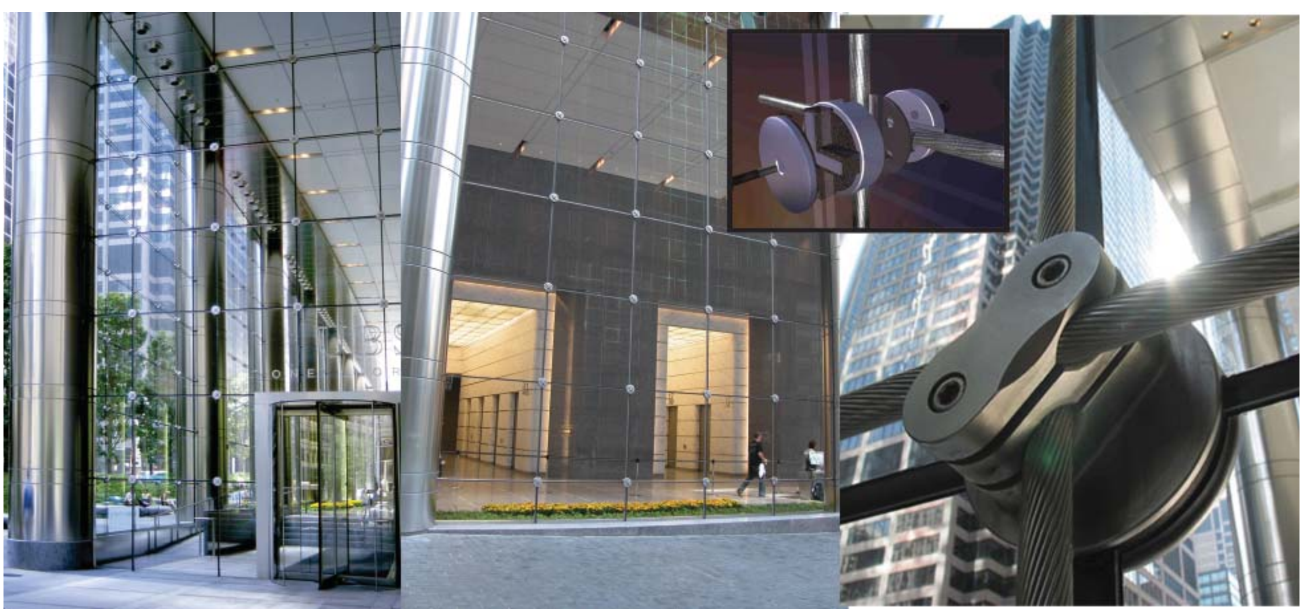

Fig.4: Cable nets top the transparency chart. Here a four-part cast stainless component clamps the cables of this flat 2-way flat cable net and clamps the glass to the net.[6]

ing curvature provides stability to the cable net that a flat net does not have, significantly limiting deflections under wind load and thus requiring lower prestress forces in the cables. Lost, however, is the facility of the orthogonal grid; the double curved net produces a variety of trapezoidal shapes that greatly complicate the requirements of the glazing system. Depending upon system geometry the corners of some trapezoids may not even lie on the same plane, resulting in the possibility that glass panels could require cold-forming during installation to conform to net geometry, thereby inducing warping loads to the glass panels. These potential affects can be mitigated through careful design of the net geometry.

Cable net structures have been used to support both clamped and drilled point-fixed glazing systems, as well as panelized systems.

Cable net structures are remarkably minimal; cables, clamping elements and glass fixing components comprise the entire structural system, and are easily the most transparent of the façade structure system types. However, this material advantage is at least partially offset by the necessary strengthening of the supporting boundary steel. The highly flexible behavior of the cable truss and cable net systems suggest that they may present performance advantages under extreme loading conditions, although research has yet to verify this hypothesis.

## SUMMARY

Structural glass façade technology provides a new vocabulary of building form to the façade designer. This paper has introduced some fundamental forms of truss and cable systems representing building-block elements within this vocabulary. The systems are presented in order of increasing transparency, an attribute unfortunately paralleled by increasing complexity and cost despite the material efficiency. Yet this technology continues to evolve, becoming increasingly diverse, efficient, accessible and economical.

This emergent façade technology presents exciting opportunities for designers willing to make a modest investment in exploring this building form. It combines proven techniques with tested materials, thus mitigating the risk of a new technology, while providing ample opportunity for the exploration of innovative building form. The technology is ready for widespread, large-scale, and varied application in the built environment.

Fig.5: Insulated glass units are point-fixed to this double-curved cable net structure at Sea-Tac International Airport in Seattle.[7]

## ENDNOTES

1. Truss Photograph from Erskine Medical Center Library, Vanderbilt University, Nashville, Tennessee. Completed 1993. Davis Brody Bond Architect.

2. Approximate deflection criteria based on the experience of the author in the design and construction of projects involving these structural systems in building façade applications. These are intended as general guidelines only. In addition to structural considerations, high deflections in the façade may be disturbing to occupants. Each individual application must be rigorously evaluated, with deflection criteria determined by a qualified registered structural engineer, and in conformance with all applicable code requirements.

3. Melarango, Michele. *Simplified Truss Design*. Krieger Publishing Company, 1981.

4. American-Yazaki 21 Headquarters Building, Detroit, Michigan. Completed 1998. Plantec of Japan Architect.

5. University of Connecticut Library Building, Stamford, Connecticut. Completed 1997. Perkins Eastman Architects.

6. UBS Tower at One North Wacker, Chicago, Illinois. Completed 2000. Lohan Caprille Goettche Architects.

7. Sea-Tac International Airport, Seattle, Washington. Completed 2004. Fentress Bradburn Architects.

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