

Context: Glass and Structure

Interwoven Strands

Structural glass facade (SGF) technology evolved from a variety of innovative experimental structures over the past three decades or more. With its roots in Northern Europe, the technology can be traced back to a few seminal projects and a handful of pioneering architects and engineers. From a broader perspective, the technology can be seen within the fabric of the built environment as a complex of interwoven strands from the same loom, the primary ones including:

- Humankind's early development of glass as a material, especially, the later development and application of glass as a transparent material in the building envelope
- The creation of inventive structural systems and their application in architecture
- The development of building forms based on extensive use of glass (i.e., the skylight, atrium, winter garden, and conservatory)
- The evolution of a performance-based architecture using the unique solar transmission properties of glass

Glass has inspired the long-term pursuit of transparency in the building envelope that has ironically masked other influences on SGF development, eclipsing them in the dominant aesthetic of literal transparency. An influence equal in importance to glass is structure; a strong bond between structure and glass characterizes SGF technology, and a

fascinating history of geometrically complex, light-weight structural systems has developed during the same period. Other influences relate to building form and application; there is an important history of the use of glass in performance applications such as solar architecture and in the enclosure of light-filled spaces such as the long-span atrium. The intertwined strands of glass, structure, and application have crossed repeatedly and to spectacular effect from a common beginning in the industrial age of the early nineteenth century.

Glass as Material

"Glass is arguably the most remarkable material ever discovered by man," states Michael Wigginton in his comprehensive book on architectural glass.¹ An estimated 4000 years ago, probably at the site of an ancient pottery kiln in the eastern Mediterranean, some curious soul stopped to wonder at the unusual properties of an inadvertent mix of sand and ash that had been exposed to the kiln's heat and ignited a love affair between humans and material, glass in this instance, that has been going strong ever since. Two millennia later, the technique of glassblowing was discovered in the first century BC on the Palestinian coast, laying the foundation for the diffusion of glass technology throughout the Roman world. The composition of glass by the time of the Roman Empire had been refined to a mix similar to the slightly green-tinted soda lime glass used today in the manufacture of flat glass: 69% silica, 17% soda, 11% lime and magnesia, and 3% alumina, iron oxide, and manganese oxide.

Glass as Architecture

The use of glass in architecture has grown steadily since its first application as window glass, dating back to approximately the first century AD. Its characteristics of color, translucency, and transparency are so uncommon that mystical properties were often associated with it by the various cultures using it. Early glassmaking processes were secrets closely guarded by governments. Glass was traded as a prized material among kings and emperors. The wealthy classes developed an appetite for glass that pushed producers to make larger and better-quality products over the centuries, a trend that continues today. Over the years, the taste for glass spread throughout the population as glass in window applications became a commodity item in Northern Europe in the late eighteenth and into the nineteenth centuries. Today, most working people value floor-to-ceiling glass in the corner office if they can get it, or at least a window if they cannot, and it is rare to encounter a residential room without at least one good-sized window. The modern manifestation of glass technology in the built environment is the glass office tower (Figure 1.1) and, increasingly, the high-rise condominium.

Glass as Window

The emergence of glass in window applications is attributed to the Roman imperial period. Window glass was first used in isolated applications, such as in the public baths to reduce air drafts. Early window glass was rather crude and unevenly translucent, as the techniques for producing transparent glass products were yet to be developed. Glass at this point was not about providing transparency or a view; it was most likely used for security and insulation from the exterior environment and for natural lighting. Then, around AD 100 in Alexandria, Egypt, an early empirical materials experimenter added manganese oxide to the melt and transparent glass was discovered. Important buildings in Rome were soon adorned with cast glass windows, as were the villas of the wealthy in Herculaneum and Pompeii.²

In spite of the poor optical quality of this early glass, the basic future architectural glass production methods were developed during this period.

Rudimentary glassblowing and casting processes were available by the first century AD, and both could be used to produce glass that was relatively flat and translucent, although its size was very limited and its thickness in both processes was difficult to control. It was not until approximately the eleventh century that Germanic and Venetian craftsmen refined two processes for producing sheet glass, both involving glassblowing techniques. One involved blowing a glass cylinder and swinging it vertically to form a pod up to approximately 10 ft (3 m) long and 18 in (45 cm) in diameter. Then, while the pod was still hot, its ends were cut off, and the cylinder was cut lengthwise and laid flat. The second process involved opening a blown glass ball opposite the blowpipe and spinning it. This process was to become common in Western Europe, and *crown glass*, as it was called, was prized for its optical properties, although its size remained very limited.

The push for transparency and increasing sheet size in glass appears to date from the beginning of its use as an architectural material. References to the various glass processes and comparisons between them often include the relative size limitations and optical imperfections.

Wigginton identifies the first true glass architecture as Northern European Gothic. Utilizing structural elements of arches, vaults, and flying buttresses, the builders of the great cathedrals of the period were able to construct stone frames, highly expressive structures, with large openings to the outside to admit light. Local climatic conditions never would have allowed for this if the openings had exposed the interior spaces to the raw elements. A robust glass technology was available to fill this need in dramatic fashion. Glass was available only in small pieces, but craftsmen had learned the recipes for producing many color variations. The window makers developed a structural system comprised of leaded bars that were used to tie a mosaic of pieces into a single membrane of glass veined with lead and capable of spanning large openings. These expansive stained-glass windows represent an early precursor to SGFs. Similarly, the morphology of the structural masonry frames with glass



FIGURE 1.1 Comcast Center, Philadelphia, 2008, Robert A.M. Stern architect.

membrane infill built around Paris from the twelfth through the fourteenth centuries heralds the new architecture that would emerge in Chicago in the late nineteenth century in the work of Louis Sullivan and others, where large glass sheets were used as infill to the new multistory steel framing systems.

Glass production and the secular use of glass increased steadily throughout the Italian Renaissance. By the eighteenth century, window glass had become a commodity item in Northern Europe. Double-hung windows were also developed in England during this period. The use of glass in architecture branched to the development of fenestration as a design element in the building elevation and to the creation of the conservatory. This later development was to have a huge influence on the future use of glass in architecture.

Glass as Building Skin

SGF technology has its roots in the great iron and glass conservatories of the nineteenth century. That century witnessed the unfolding of the industrial age and the introduction of metal to architecture with such dramatic examples as the Palm House at Bicton Gardens by D. and E. Bailey (based on designs by John Loudon), the Palm House at Kew Gardens by Richard Turner and Decimus Burton, and Joseph Paxton's Crystal Palace.

The conservatory structures in Europe and England are a dramatic departure from masonry architecture, where heavy masonry walls act as both weather barrier and load-bearing structure, instead adopting structural iron framing systems that allow for far greater design freedom. The weather barrier is provided simply by draping a nonstructural cladding material (glass) over the structural framing system: a building skin. Glass as building skin was made possible by the age of steel that emerged from the Industrial Revolution. Cast and wrought iron replaced the lead bars of the Gothic cathedral windows, allowing for the construction of complete enclosure framing systems comprised of slender metal components. Glass was easily attached to these frames. Quite suddenly, building enclosures could be transparent, clad entirely in glass. This

development set the stage for the Modernists of the twentieth century and the advent of high-rise towers sheathed in glass.

In the first half of the nineteenth century, conservatory structures flowered under the influence of such designer-gardener-builders as J.C. Loudon and Joseph Paxton. The conservatories were impressive as performance-based architecture responding to the demanding requirements of the exotic botanical species they housed, entirely free of the prevailing conventional masonry architectural style of the period. With little in the way of prior art, the pioneers in this new building form proceeded intuitively with the development of the structural systems. They created slender wrought iron bars and methods to connect them. The structures were so minimal that in certain instances the literature of the time describes them as deflecting in light winds until the glass was affixed to the frame. The glass was actually being used as a stressed skin to stabilize the structure. These innovators were far ahead of their time in using glass as a structural element, even before the advent of glass-strengthening techniques.

While the building form represented by the conservatory structures quickly transcended its early botanical applications to become an important public structure type, perhaps as best represented by the Crystal Palace, there was little integration of this building form with the conventional architecture of the time.³ The great conservatories were largely freestanding autonomous buildings. Certainly they inspired, just as they continue to inspire new generations of designers today. Equally certainly, they continually increased the desire for and use of glass in architecture.

Meanwhile, in the great cities of Europe and America, density and land values were creating pressure to build upward, pushing the limits of the predominantly masonry building practices of the time. By the end of the nineteenth century, a Chicago engineer named William Jenney had devised a method of steel framing and thus gave birth to the technology of high-rise buildings. Exterior walls became functionally different in a significant

way; like the earlier iron framing systems used in the conservatory structures, they were no longer load-bearing, carrying only their own weight over a single-story span. They no longer needed to be masonry (although masonry remained the predominant wall material for years to come); in fact, masonry was an inappropriate material for most of these new applications because it was unnecessarily heavy.

The Advent of the Curtain Wall

The use of glass as a predominant element of the building facade exploded in the twentieth century, fueled by Modernism, especially post–World War I Modernism, and the development of steel frame structures, improving sources of glass supply, and the development of curtain wall cladding systems. Visionary designers and tradesmen produced a relatively small number of landmark buildings in the first half of the century utilizing these new materials and processes, paving the way for the paradigm shift that was to come in the 1950s, when the modern curtain wall industry was born. Stunning and influential architectural innovations like the Bauhaus Building in Dessau by Gropius in 1926, the Seagram Building in New York City by Mies van der Rohe in 1954, and the Lever House by SOM in 1952 were among these early buildings.

Flat glass for architectural applications is produced today through the float process. Invented by Alastair Pilkington⁴ in the 1950s, the process was commercially viable by the early 1960s. The float process provides the convenience of making glass horizontally, similar to the older casting processes. In the older processes, the bottom side of the cast glass sheet suffered from poor surface quality that could only be remedied by expensive grinding and polishing. The float process solved this problem by floating the liquid glass on a bed of molten tin. The resulting product is flat, smooth, and transparent, the recipe for high optical quality. The float process provided the fabrication technology required for the next boom in the use of glass in architecture, replacing the drawn glass process of the time.

Glass was thus becoming increasingly available and economical. The new steel-framing technology opened the door to a dramatic use of glass as a predominant element in the building skin. Designers were struggling with solutions to replace the masonry practices dominant at the time. In the early twentieth century, aluminum was becoming available in larger quantities at lower cost. By the 1920s, this material was beginning to see significant use in architecture.

The required infrastructure was thus in place, and the post–World War II boom in America and Western Europe resulted in an explosion of high-rise curtain wall buildings. Commercial developers found in the emerging technology low-cost solutions for maximizing leasable square footage in a given building footprint. Unfortunately, most of these solutions lacked both the design sensitivity and the quality of the early Modernist work, becoming what Wigginton refers to as “a sort of ‘International Style’ without the style.” The result was a proliferation of sterile-looking, water-leaking, energy-hogging glass towers redefining the skylines of the world’s great cities (Figure 1.2). Regardless, it significantly boosted the glass and curtain wall industry.

Curtain Walls and SGFs

While closely related, there are distinct differences between curtain walls and SGFs. The primary difference is in the structural systems used to support them. Aluminum extrusions are generally used in curtain wall systems to construct a frame that secures some type of panel material, ranging from glass to composite metal panels and stone. The frame may be expressed or completely covered on both the inside and outside of the building. Curtain wall framing systems typically span only from floor to floor, the primary spanning member being the aluminum extrusion. Both the curtain wall and the SGF are separate from the building framing system but attached to and supported by it.

SGFs are often used in longer spanning applications where an aluminum extrusion as the primary spanning member becomes impractical or impossible. The technology embraces a design objective



FIGURE 1.2 The monoliths of highly reflective glass spawned by cheap curtain wall cladding systems did little to enhance the urban environment.

of high transparency and expressed structure incorporating some type of glass, most frequently clear glass often used without any framing elements, as the cladding material. A variety of structural options are available to accommodate a range of spanning conditions as described. The structure is exposed and thus becomes a dominant element of the facade design. Emphasis is often placed on the detailing and craftsmanship of the structural system. There has been a consistent evolution toward a dematerialization of structure, paralleled by an increasing refinement of the structural systems and components. Tensile elements have become increasingly predominant, leading to the development of pure tension-based structural systems like cable nets. Frameless glass systems, commonly referred to as *point-fixed* or *point-supported systems*, are most often used for the same reason. Framed panel or stick-type systems utilizing aluminum extrusions are also used quite effectively in SGFs but typically benefit from a design integration with the structural systems that support them, differentiating them from conventional curtain wall systems, although off-the-shelf curtain wall systems can be and have been used in SGF applications (Figure 1.3).

Another difference is in the strategy employed to provide the weather seal. Contemporary curtain walls typically employ a rain-screen strategy utilizing dry gaskets to provide the primary weather seal. These wall systems employ complex designs of aluminum extrusions that attempt to provide a pressure-equalized cavity, or cavities, as a barrier to water penetration and air infiltration. The design is intended to allow pressure differences to equalize within the extrusion cavities so that even if water penetrates the cavity, it will drain out of the system and not penetrate to the inside. Consistent with a minimalist approach, the weather seal typical of the glazing systems used on SGFs is a slender joint of silicone, field applied between adjacent glass panels; as with the structural systems, nothing is hidden. Today's silicone sealants are high-performance materials providing an effective, reliable, and durable weather seal.

Solar Architecture

A noteworthy parallel to the evolution of curtain wall technology, identified and developed by Wigginton, is the application of glass architecture as a potentially energy-efficient and environmentally responsive building form. This development also flows from the conservatory structures of Paxton and his contemporaries. Ecological function was their purpose; the enclosures were intended to sustain the botanical species collected from tropical areas of the planet in the less favorable climate of England and Northern Europe. These engineer-gardeners, or gardener-engineer in the case of Paxton, developed surprisingly sophisticated environmental systems including natural ventilation and thermal control, but the indispensable material was glass, which



FIGURE 1.3 The Walter E. Washington Convention Center in Washington, D.C., 2003, is enclosed by an exposed truss system supporting an off-the-shelf stick curtain wall system. TVS-D&P-Mariani, PLLC JV architects.

enabled the construction of the solar collector otherwise known as the *conservatory*, *winter garden*, or *greenhouse*.

Designers who continued to experiment with solar architecture through the first half of the twentieth century were making use of the predominant attribute of glass, its transmittance, in quite a different manner than those architects who were pursuing transparency as an architectural concept. This group had recognized the powerful performance potential of glass, and thus utilized transparency largely for performance as opposed to aesthetic or conceptual reasons. The evolution of solar architecture quickened throughout the 1950s and 1960s, with many examples of solar homes and other buildings bringing increasing awareness of this building form even among the general population, especially after the renewed concern for conservation and energy efficiency in the wake of the 1972 oil crisis.

Thus, the development of transparency in the building envelope was pursued early on as a performance attribute, not just as an aesthetic intent or a conceptual principle. Glass in buildings has a long history of use for the purpose of harvesting solar energy. This has renewed the potential for high-performance contemporary glass products to play a key role in reducing energy use and even achieving net-zero energy consumption in today's buildings. Glass, as a mechanism for solar control, and SGF technology were parallel developments with little crossover in the early decades of the technology. Many SGFs were built with little or no regard to thermal performance and energy efficiency; heating, ventilation, and air conditioning (HVAC) systems were simply sized to compensate for thermal gain or loss. This is true even of prominent facades built in recent years in the United States. Increasing pressure for improved performance of the building envelope is now bringing long overdue change to facade technology, and the emphasis on energy efficiency and thermal comfort holds promise for better-performing future applications of SGF technology. In fact, the technology is increasingly being used in multistory double-skin facade systems, as is evidenced in the case studies in Chapters 7 to 17.⁵

The Atrium

Another building form deriving from the nineteenth-century conservatory structures and combining exposed structure and glass is the atrium, which emerged in the late twentieth century. Atriums were sometimes used to enhance the climate of an enclosed space, but most frequently they were used simply for the dramatic space they provided, such as the spectacular atriums that characterize the hotel architecture of John Portman. Richard Saxon maps the emergence and development of the atrium in detail in a book devoted to the subject.⁶ SGF technology is ideal for application in atrium enclosures.

The Art of Structure

Long-span glass facade technology has resulted from the integration of a highly engineered glass material with elegant exposed structural systems. The rapid development of this technology over the past 40 years or more has been driven primarily by the pursuit of transparency in the building envelope, but this has enabled the development of the remarkable structural systems that have become the hallmark of SGF technology. Inventive structural systems have been the passion of creative engineers dating at least to the early to mid-eighteenth century and the work of J.C. Loudon, Joseph Paxton, and Richard Turner, who were each involved in developing structural systems and even patenting components. The great iron and glass conservatories of this period were most notable for the extensive use of glass, but this was only made possible by the transformation of the new wrought and cast iron materials into suitable structural systems—and quite elegant systems they often were.

The Crystal Palace set the precedent for the Universal Exposition, or World's Fair, as a showcase for structural innovation, followed by the Eiffel Tower at the Exposition Universelle of 1889 and the Ferris wheel at the Chicago World's Fair in 1893. The Russian engineer Vladimir Shukhov was designing and building gridshell structures before the turn of the twentieth century. Alexander Bell was experimenting with space structure geometries at approximately the same time. The Palace

of Horticulture at the Panama-Pacific International Exposition in San Francisco (1915) followed, and so on to Expo '67 in Montreal featuring the iconic geodesic biosphere dome by R. Buckminster Fuller, which was a major coming-out party for space truss systems with several large pavilion constructs. Lev Zetlin's bicycle wheel roof for the New York Pavilion at the New York World's Fair (1964) stands among this lineage of novel structures, as does the British Pavilion by Nicholas Grimshaw with engineer Ove Arup at Expo '92 in Seville. The Olympic Games have also been a showcase for the art of the engineer, such as at the Munich Games in 1972 with the spectacular cable net structures by Gunter Behnisch with Frei Otto.

Most structure in architecture is ultimately concealed. These public venues have provided some of the few opportunities creative engineers have had to express their art. Then came the Modernists in the early twentieth century with their visions of transparency and a gradually emerging glass and structure technology to convert these visions into reality. By the 1960s, the infrastructure of materials and processes was in place to transform the building skin and bring a remarkable vocabulary of transparency to architecture. Structure started to show through the transparent envelope, and a new appreciation for the expression of structure as an aesthetic element of the design emerged.

The emergence of highly transparent glass facades that started in the 1960s and 1970s created one of the greatest opportunities ever provided the inventive structural engineer. What better way was there to showcase a structure design than to literally put it behind glass, like fine jewelry? Never mind that the overriding design intent was transparency and the dematerialization of the structure; this simply resulted in more refined and elegant designs. It was about transparency, but suddenly the budget was there for machined and cast stainless steel components. Transparency produced unanticipated side effects; the structure systems were getting smaller, yet more visible at the same time, drawing attention in their sparseness like a candle flame in the darkness. Almost imperceptibly, transparency

focused on structure and the engineer had moved into the spotlight.

Ultimately, the design intent of transparency did dramatically dematerialize the structural systems, reaching its current minimalist expression with cable supported facades. But what has emerged simultaneously is a remarkable diversity of innovative glass facade and enclosure designs where the structure is showcased, what Nina Rappaport refers to as "the integration of structure as decoration," which she calls "deep decoration, or beyond surface . . . the structure has design emphasis."⁷ Thus, a major aspect of the technology, the function, and the appeal of SGF is not transparency, but the structure itself; transparency becomes a means of showcasing structure. Consideration of the applications built to date reveals that the structural system used in support of the facade is, with some consistency, the most distinguishing component.

These divergent but related developments in architectural glass, steel structural systems, conservatory enclosures, atriums, solar architecture, and facade systems began to converge in the late twentieth century into a long-span glass facade building form. It is interesting to note that innovations in technology have consistently paced this building evolution. The introduction of wrought and cast iron, the production sources for glass and aluminum extrusions, and the development of structural steel framing systems all predated the development of curtain wall systems by several decades. The same is true with the development of glass as a structural material. The tempering or toughening process for glass was invented in 1928 in France but took several decades to gain traction in the marketplace. By the 1960s, the suspended glass mullion walls that presaged Foster's Willis Faber & Dumas Building (1975) had started to emerge as a building form. But it was not until Pilkington developed and engineered a warranted product for use on the Willis Faber & Dumas Building that this technology came into widespread use. This trend continues today; advanced interlayer materials, for example, are enabling ever-more-aggressive application of glass as a structural material.⁸

The Evolution of SGFs

To a notable extent, historical growth in the architectural glass market has been driven by a series of high-profile applications with widespread impact, including the great windows of the Gothic cathedrals in Europe followed by the transition to widespread secular use of glass in buildings and such milestones as Hardwick Hall (1590–7) by Robert Smythson and the new wing at Hampton Court (1689–96) by Sir Christopher Wren. Many if not most of these milestone projects were made possible or were inspired by advances in glassmaking technology, but it is ultimately the architectural manifestations that inspire broader adoption and use, as with the great burst of glass conservatory construction in nineteenth-century Europe and England that so strongly influenced architecture and set the bar for decades to come in glass structures.

Emergence

In a manner similar to that documented above, certain high-profile instances of SGFs mark the emergence and progression of the technology.

With the French invention of the process for heat-strengthening glass in the late 1920s, the material elements were in place for the initial emergence of SGFs: steel framing techniques and tempered glass. Yet, the exploitation of these materials was several decades away. By the 1950s the French, appropriately, had also conceived the long-span frameless glass facade. The Hahn system used at the Maison de la Radio in Paris in 1953 involved large glass plates two stories high. This is a very early example of a suspended glass facade. The glass is clamped and hung from the top edge. Glass fins set perpendicular to the facade at the glass joints are used to provide lateral stiffness.⁹ This concept quickly diffused into the marketplace, resulting in the construction of many similar facades during the 1960s.

The progenitor of the immediate line of SGF technology may very well be the Willis Faber & Dumas Building in Ipswich, England (1975), by Foster Associates. Wigginton cites the landmark glass facade of this building as completing a “particularly

thematic journey in glass architecture,”¹⁰ referring to Mies van der Rohe’s 1922 office tower concept model referred to above as the start of that thematic journey. The end of one journey can be the start of another, and such a case can be made here. Although other suspended glass walls were completed before this one, the Willis Faber & Dumas Building, for various reasons, became an icon inspiring future SGF innovation.

Sweeping walls of glass with little or no apparent means of support are so common now as to attract little attention. Such was not the case in the 1970s. Unlike the glass office tower, the facade for the Willis Faber & Dumas Building is not about transparency but rather reflection, at least during daytime. The glass is coated with a bronze solar control coating, presenting a solid, uninterrupted reflective exterior face (the weather seal is provided by a slender field-applied flush silicone joint). From inside the wall is almost entirely transparent, and at night with the interior lit, the glass wall virtually disappears. As with the Hahn system some 15 years earlier, the glass for the Willis Faber & Dumas facade is hung from above, only instead of a single sheet, six sheets are linked together in a chain from top to bottom, in this respect creating perhaps a truer “curtain” wall than the technology commonly referenced by that term. Glass fin elements set perpendicular to the glass plane on the vertical glass grid provide lateral support. The facade is 39 ft (12 m) high and follows an irregular curve in plan. In addition to Foster, Martin Francis played a role as glazing consultant in the realization of this facade, and Pilkington fueled design innovation by providing the suspended glazing system as a product, at a competitive price and with an unprecedented warranty. The early Pilkington system used a patch plate to accommodate the fixing of the glass. From this time on, mechanical point-fixed glass systems became a driving force in the evolution of SGF technology. This project is featured as a case study in Wigginton’s *Glass in Architecture*.¹¹ Suspended glass fin facades¹² thus initiated the evolution of SGF technology and are to this day perhaps the most commonly found type of high-transparency facade.

Milestone Applications

The evolution of SGF technology can be viewed in a series of high-profile applications. A few of the most significant of these follow.

Willis Faber & Dumas Building; Ipswich, England

Glass Fin Facade

Foster Architects, designed 1971–2,
completed 1975

The Willis Faber & Dumas Building (Figure 1.4) is significant in many respects. It is one of the very early examples of a frameless suspended facade incorporating glass fins as a stiffening element against lateral loads. It represents the productive partnership between industry and architecture, with the first application of a new product technology provided by Pilkington, a leading glass producer. It popularized this facade type, leading to a

proliferation of applications. It is a viable candidate for defining the birth of SGF technology, as articulated in *Glass in Architecture*.¹³

Garden Grove Church; Garden Grove, California

Glazed Space Frame Enclosure

Johnson/Burgee Architects, designed 1977–8,
constructed 1978–80

Popularly known as the Crystal Cathedral, this building obviously finds its roots in the great iron and glass conservatory structures of mid-nineteenth-century Europe. Predating the development of the lighter tensile structures that would emerge over the next decade in facade applications, this design makes use of a space frame structural system. The structure is clad entirely in reflective glass using a panel system in which the glass is structurally glazed to an aluminum frame. The



FIGURE 1.4 The Willis Faber & Dumas Building, Ipswich, England, Foster Architects, 1975. The glass facade marks the birth of SGF technology.

facade system includes operable vents that provide natural ventilation to this large glass enclosure (Figure 1.5).¹⁴

Glass Walls (Les Serres)

Parc de la Villette, Paris

Architect Adrien Fainsilber with Rice Francis Ritchie (RFR), designed 1983, constructed 1984–6

Les Serres was a seminal project for SGF technology incorporating many innovations and indicating the direction for future work. Peter Rice conceived of *cable mullions* as a means to achieve optimum transparency (Figure 1.6). Les Serres features horizontal rod trusses mounted on a steel pipe frame. The design team developed a special glass bolt called a *rotule*, which provides for unrestricted rotation at the point fixing, thus eliminating bending moments on the glass. This project is discussed further in Chapter 3.

The Pyramids at the Louvre, Paris

Grand Pyramid

I.M. Pei architect with Nicolet Chartrand Knoll, Ltd., and RFR, designed 1983–5, constructed 1986–8

Inverted Pyramid

I.M. Pei architect with RFR, completed 1993

The space grid structure was novel at the time in its extensive use of tensile elements.¹⁵ The structure is clad with a fully perimeter-supported structurally glazed system in which the glass is fixed to the frame by a structural silicone adhesive with no mechanical attachment. The Louvre Pyramid served to popularize the emerging new SGF technology (Figure 1.7). The structure is one of the first to make use of a “superclear,” virtually colorless glass that is further discussed in Chapter 2 as low-iron glass.¹⁶ RFR was subsequently asked to design the structure and glazing for the smaller Inverted Pyramid below the courtyard at the Louvre (Figure 1.8).

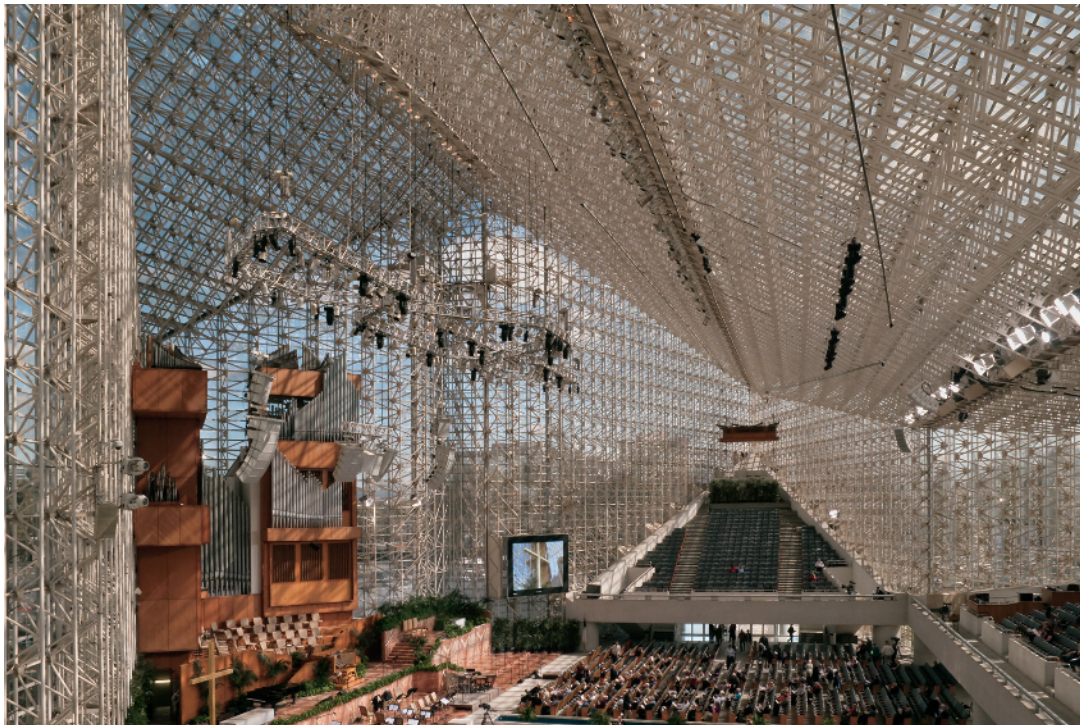


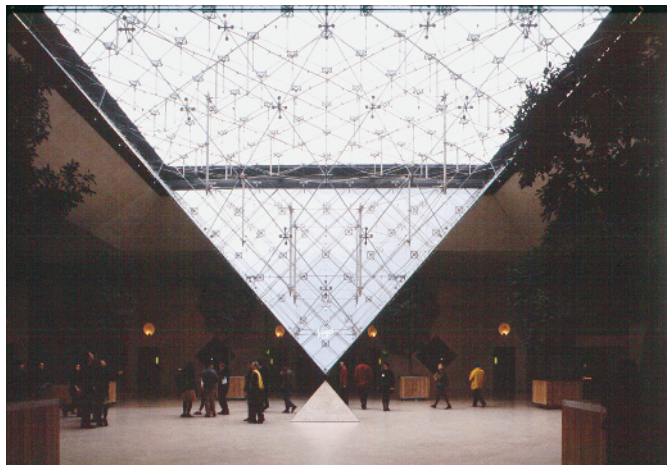
FIGURE 1.5 Crystal Cathedral, Garden Grove, California, 1980, Johnson/Burgee Architects. A reflective glass-clad space frame provides the enclosure for the Garden Grove Church.

FIGURE 1.6 Glass Walls (Les Serres), Parc de la Villette, Paris, 1986, Adrien Fainsilber, architect, with Rice Francis Ritchie (RFR). Peter Rice conceived the cable mullion as a means of optimizing transparency.



FIGURE 1.7 The Louvre Pyramid, Paris, Pei Cobb Freed and Partner with Nicolet Chartrand Knoll, Ltd., and RFR, 1988. The Pyramid did much to popularize the emergent technology of SGFs.

FIGURE 1.8 The Inverted Pyramid, Paris, 1993, Pei, Cobb, Freed and Partners with RFR.



Reina Sofia Museum of Modern Art, Madrid

Vertical Circulation Towers, completed 1990
Ian Ritchie Architects

After participating in the Louvre Pyramid and Les Serres designs with RFR, Ian Ritchie with Ian Ritchie Architects was asked to design three 115 ft (35 m) tall glass circulation towers as part of an effort to visually redefine this historic building, originally built in the eighteenth century as a hospital. Minimalism, transparency, and modernity were among the guiding principles of the design. The glass envelope encloses the vertical steel tower structure but sits well away from it, emphasizing the separation between skin and structure. The Pilkington Planar point-fixed glass is supported by an innovative tensile structure suspended from cable-stayed outriggers at the top of the tower. The tensile structure is

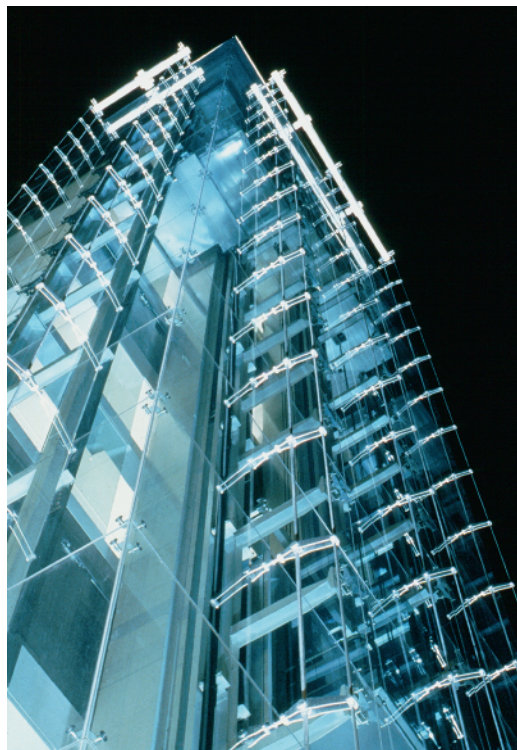


FIGURE 1.9 Reina Sofia Museum of Modern Art, Vertical Circulation Towers, Madrid, 1990, Ian Ritchie Architects. The innovative glass enclosures were widely publicized, influencing many of the advanced facade applications that emerged in the following decade.

outboard of the glass skin, and is comprised of stainless steel rods that anchor to large spring assemblies at the base of the tower to reduce the loads transmitted to the tower structure. The tie-downs support steel plate armature assemblies that reach out and support the glass fixings at the vertices of the glass grid (Figure 1.9). The towers were widely publicized because of the extraordinary degree of transparency achieved with the enclosure.

Kempinski Hotel, Munich

Cable Net Facades, completed 1993
Murphy/Jahn Architects with Schlaich Bergermann and Partner

This is widely recognized as the first cable net facade, conceived by engineer Jorg Schlaich of Schlaich Bergermann and Partner, a leading engineering firm in the development of SGFs. Another bold and seminal structure, the cable net is comprised of prestressed vertical and horizontal cables in a planar configuration. The glass is clamped to the net and butt-glazed with silicone to provide the weather seal. The structures enclose opposing sides of the hotel lobby (Figure 1.10).

Messe-Leipzig Glass Hall and Bridges, Leipzig, Germany

Vaulted Glass Enclosure
Gerkan Marg & Partners and Ian Ritchie Architects, with IPP Ingenieruburo and HL-Technik; design started 1992, construction completed 1995

The monumental Messe-Leipzig vaulted glass hall is 780 ft (238 m) long and 262 ft (80 m) wide, with a maximum height of 92 ft (28 m). The vault structure is hierarchical, with primary arch trusses on 82 ft (25 m) centers supporting an orthogonal grid shell of welded tube steel. A low-iron glass skin is hung from the structure, point-fixed and tied back to the gridshell with long-fingered cast components (Figure 1.11). The project received international recognition on the opening of the facility in 1996 and spawned further applications of SGF technology.

This is just a small sampling of a few early milestone projects and a brief overview of the many fascinating applications of SGF technology.



FIGURE 1.10 Cable net facades at the Kempinski Hotel, Munich, 1993, Murphy/Jahn Architects. This is the first application of a flat cable net as a glazed facade structure.



FIGURE 1.11 Messe-Leipzig Glass Hall, Leipzig, Germany, 1995, Gerkan Marg & Partners and Ian Ritchie Architects. The monumental glass vault is another milestone in the evolution of SGFs, widely publicized and influencing future applications.

■ Innovator and Enabler

Implementers and enablers are found at the leading edge of any innovative and emergent technology such as SGF technology. Prominent among them is Tim Eliassen, a founder of TriPyramid Structures, a company specializing in the design and fabrication of rod and cable rigging systems and their application in SGFs.

Technology transfer is a well-established pathway for innovation. Tim Eliassen blazed a trail in bringing the technology of high-performance sailboat rigging to the architectural market. Since that time, there have been few milestone SGF applications with which he has not been involved.

Eliassen's undergraduate study was in aeronautical engineering, shifting to nuclear reactor engineering with his graduate work. But his passion was for sailboats. Recognizing an opportunity for improving the design of rigging systems, Eliassen cofounded Navtec and was immediately immersed in the world of large racing yachts, America's Cup boats, and sailing vessels whose sole purpose was complete circumnavigation of the globe in the shortest possible time. In the 1980s, Eliassen met Martin Francis, an architect and the F in RFR, the architecture/engineering firm he founded with Peter Rice and Ian Ritchie. Francis also happened to be a designer and builder of large sailing yachts. Their meeting was the beginning of an ongoing dialogue about the possibility of applying the rigging technology of high-performance sailing yachts to buildings. During the course of this dialogue and developing friendship, Francis took Eliassen to see the Glass Serres at Parc de la Villette, the seminal work designed by Peter Rice and RFR in 1983.

Then in 1987, Eliassen received a call from Francis telling him that there was a project in France that needed his involvement: the Louvre Pyramid by I.M. Pei. The project introduced Eliassen to architectural considerations of exposed structure and visual transparency with a focus on tension elements and, perhaps most of all, connection details. Under Eliassen's direction, Navtec ended up delivering what he refers to as "short pieces of yacht rigging," some 3800 of them, for the construction of the Pyramid structure. (The word *short* is a reference to the fact that the cold-headed rod rigging Navtec provided to the yachting industry was typically in lengths far longer than those required for the Pyramid.)

While not the first project to make predominant use of tensile elements, the Louvre Pyramid is a milestone SGF project important in two respects: it served to popularize the building form in the international design community and it revealed to Eliassen a compelling business opportunity. Eliassen had ended his ownership of Navtec by this time while remaining with the firm, focused on the design and engineering of the rigging systems, his true passion. On the successful completion of the Louvre Pyramid, he promptly recommended to Navtec's management that a new division be launched to pursue opportunities in the building marketplace. Management was less than enthusiastic about the idea ("roofs leak; you get sued").

Eliassen founded TriPyramid Structures in late 1989 with Michael Mulhern, who had acted as project manager for Navtec on the Louvre Pyramid project. Their first in a long line of high-profile projects was Moshe Safdie's Montreal Museum of Art. TriPyramid worked

with Mero, then a provider of space frame structures, in developing an interesting hybrid space frame solution for a museum skylight in which many of the typical pipe elements were replaced with stainless steel tension rods and custom fittings, lightening the structure and enhancing the transparency.

Eliassen has a strong performance orientation deriving from his work with racing yachts; his success was measured not by the appearance of the work, but by the effect on performance. “It was simple with the boats,” comments Eliassen; “if you get the detail right, the boat goes faster.” This performance orientation served him well in his work on buildings, producing a performance-based aesthetic that was readily embraced by the design community. Well-designed exposed structures express a diagram of forces, providing rationality to the structural form that many find aesthetically pleasing. With Eliassen, this extends right down to the connection details, his particular passion. The component designs that characterize his work are elegant mappings of the functional requirements imposed upon the work.

TriPyramid was founded at a time when computer-aided design/manufacturing (CAD/CAM) technology was emerging, with companies like Navtec being far ahead of typical companies in the building industry. The ability to assemble a three-dimensional model and drawing package differentiated TriPyramid from other fabricators serving the construction industry at the time. Eliassen anticipated leveraging this capability in the marketplace as a means to supply rigging systems for buildings. But the business quickly changed.

New associations with such leading-edge glass designers as James Carpenter and Tim Macfarlane drove the business in the direction of art glass and other experimental structures, innovative explorations in steel and glass that pushed the materials and processes and increasingly involved Eliassen as a key collaborator in the design and development process. These investigations were most often driven by the pursuit of transparency and a dematerialization of structure that was greatly facilitated by Eliassen's knowledge of and experience with the workings of high-strength tensile components. The business of TriPyramid became the integration of these elements into architectural structures.

Eliassen recognizes intense collaboration as a hallmark of innovation, referencing Peter Rice as an extraordinary collaborator. The details of the cable wall on architect Rafael Viñoly's Kimmel Center for the Performing Arts in Philadelphia were developed in an intensive half-day collaborative session involving Viñoly, his facade wizard Charles Blomberg, Eliassen, and structural engineer and facade designer Tim Macfarlane. Dozens of projects later, with many landmarks among them, Eliassen still finds his music in the details. “The irony is that the lighter and more transparent you make a structure, the more prominent the details become,” he observes. When considering pushing the boundaries, as often happens with SGF projects, there can be enormous value in having an experienced innovator on the team. That is why Eliassen has participated in many of the projects referenced in this book, including several of those described in the case studies in Chapters 7 to 17.¹⁷

Implementing Innovative Building Technology

The construction industry remains fragmented, highly conservative, and myopically risk-averse, showing little of the progress that has characterized other economic sectors, such as the automotive industry. This situation may finally be changing; such emergent and rapidly developing technologies as building information modeling, new strategies for prefabrication, and novel project delivery strategies may well revolutionize construction practice.

The relevant consideration here is the project delivery strategy. The evolution of SGF technology is documented in a series of highly innovative applications, each building on the antecedent work. The nature of current construction practice makes it an extremely challenging environment for innovation. Projects with innovative content—in design, materials, or processes—must embrace carefully crafted implementation strategies if they are to succeed. Central to any such strategy is the involvement of the appropriate experts for design, fabrication, and installation *as early as possible* in the design process. The prime motivation for alternate delivery strategies, at least when it comes to advanced facade technology, is to facilitate the earliest possible involvement of such experts.

The traditional design-bid-build process is seldom appropriate to even the simplest SGF applications. Years ago, a variation of the design-build process ultimately found favor in advanced facade projects where specialty design and engineering services were required. Rather than providing completed contract documents for the specialty system, the architect produced representative design development drawings and a performance specification, with final detailing and engineering falling to a specialty contractor. Today, even with a conventional design-bid-build project, the SGF work is most often broken out as a design-build package. However, this is often inadequate to a project's needs because the required expert cannot be properly engaged until the designer-builder is selected.

The design-assist strategy was developed by the American Institute of Architects (AIA) to address this shortcoming. Design-assist allows the

project team to hire a material supplier, fabricator, or contractor early in the design process as a paid consultant. This practice is relatively new, and its use varies widely among projects. Many developers distrust it, fearing that it will compromise the provision of optimally competitive services. Many supply-side practitioners misunderstand the process, thinking that their usual presale services constitute design-assist. Nonetheless, this strategy is being effectively applied with increasing frequency, as many of the case studies in this book attest.

A design-assist strategy does not assure the service provider of securing a design-build contract for the work. Consequently, some specialty contractors are reluctant to provide such services unless they improve their prospects for obtaining a construction contract. One successful solution to this impasse is to guarantee a design-build contract to the design-assist provider if, at the completion of the design-assist phase, this entity provides a complete construction proposal that meets a preestablished budget. Other conditions are often incorporated in the design-assist agreement. Integrated project delivery (IPD) is a more sophisticated and comprehensive project delivery strategy being developed by the AIA that incorporates a significantly different contracting strategy intended to provide a collaborative project environment that fosters the early involvement of all required experts.

The important point here is that each SGF project must be carefully assessed for innovative content and relative complexity. As the technology matures, applications of low to moderate complexity with no significant innovative content are increasing, indicating that SGF technology is slowly diffusing into the marketplace as a new tier of adopters is enabled by the prior work. With simple applications and a design-build delivery strategy, little or no pre-bid involvement by a specialist may be required, although input from a specialty contractor, including preliminary pricing, is strongly recommended on even the simplest SGF projects. Most projects, however, will have enough complexity and novelty that the early involvement of the required specialties will be of significant benefit. Many SGF projects will continue to push beyond prior art, achieving a level of innovation

that makes the early involvement of appropriate specialists critical to the success of the project.

The TKTS project, the case study presented in Chapter 17, is an excellent example. Architect Nick Leahy with Perkins Eastman characterizes an innovative SGF project, here the all-glass TKTS enclosure:¹⁸

As with any innovative project, it [TKTS] builds on pioneering concepts that are out there but either amplifies, refines or redefines them to produce a new product or uses, and in this way the technology and line of innovation moves forward a little. Structural Glass technology and architecture have advanced quickly over the last 15-years, and there are some beautiful structures built that served as precedents and drivers for design solutions. While working on the project, there wasn't a book on glass I didn't read or a new all-glass project I would not go to see and study the details.

Structurally we started with calculations and based the design on built concepts and then pushed the boat out a little further. Dewhurst [the structural engineer] had recently completed a house with a load bearing glass wall supporting steel beams, so they had experience in the performance of glass under loads, and the precursors to the beam design were various glass fins and structural fins designed for curtain walls and roofs.

The challenges of implementing innovative SGF technology are increased by the unique, one-off nature of each application combined with a frequent lack of significant resources for research and development, including mockups and testing. Leahy further comments:

In an ideal world we would have had an R&D budget for the project, but because of the nature of the project and the complex client structure, this wasn't the case. Architecture is a very different process than say product design, where you would build a prototype and then go to production; in architecture every project is a prototype....

Leahy attributes much of the success of the TKTS project to the early involvement of key consultants, material suppliers, and fabricators, as discussed in Chapter 17.

Organization of System Types

SGF technology is comprised of structural systems, glass, and the glass-fixing systems that bind structure and cladding. The facades are most usefully categorized by the integral structural systems used to support them. The elements of glass and glass systems are explored later, but are deemed subordinate to the structure system type with respect to facade type categorization. Thus, a long-span glass facade supported by a cable truss system becomes fundamentally a cable truss facade, regardless of whether it supports a spider-fixed frameless glass system or a framed unitized system, or whether it is clad in superclear or highly reflective glass. While the glass system is often tightly integrated with and even part of the structural system, it is generally the structure designs that represent the core innovative content of this building form.

Common Attributes

As a group, the structure system types that have been used in the construction of long-span glass facades frequently display certain general characteristics that help to define this class of building technology (Table 1.1).

TABLE 1.1 Common Characteristics of Structures Used in SGFs

Design aesthetics	Exposed and expressed structure
	Expression of membrane
	High transparency
	Dematerialization of structure
Materials, process, systems	Refined craftsmanship
	Machined and cast components
	Quality materials and finishes
	Lightweight structural systems
	Predominant use of tensile elements
	Use of tensile structures (all tensile elements)
Structural design and behavior	High structural flexibility
	High deflections
	Prestressed systems

Structure Types

The following structure types are considered because they have been used or could potentially be used in SGF applications:

- Mullion
- Glass fin
- Simple truss
- Guyed strut and mast truss
- Cable truss
- Gridshell
- Space truss/space frame
- Tensegrity
- Cable

The structural systems are not unique to the larger vocabulary of structural form, but their use in long-span glass facade applications has resulted in novel adaptations, and they can now be recognized as a unique class of structure types. The identification and comparison of the basic structure types are facilitated by their reduction to an elemental form, considered here in a simple vertical wall application. They are, however, derived from a rich body of innovative built facades of remarkable diversity and

complexity, some of which defy such reductive analysis. This is symptomatic of a vital technology that is still evolving, recombining, and producing new forms.

Morphology

Morphology refers to the structural form that differentiates the system types discussed in the following chapters. While the real-world applications are diverse, each structure type displays a characteristic fundamental form and a unique general aesthetic. Table 1.2 groups the structure types into broader categories for purposes of organization.

Open and Closed Systems

Two distinct classes of structure systems are used in SGFs: closed and open systems. The attribute that differentiates them in this classification is the requirement for prestress, which must be initially determined as a parameter of the design process and must be realized on site during the installation of the structure. Prestress requirements have potentially significant implications for the design, engineering, fabrication, installation, and cost of an SGF, and thus become an important consideration in system evaluation, selection, and application.

- *Closed System:* A structure whose primary stability is achieved internally, independent of load transfer at the boundary structure anchorage

TABLE 1.2 Grouping of Basic Facade Structure System Types

Linear systems (Chapter 3)	Mullion systems	Linear open or closed section Glass fin
	Truss systems	Simple truss Guyed strut, mast truss Cable truss
Reticulated spatial systems (Chapter 4)	Space grid structures	Space frame with moment connections Space truss with pinned connections
	Gridshells	Quadrilateral gridshell Triangulated gridshell
	Cable-strut systems	Externally stabilized Internally stabilized, tensegrity
Cable systems (Chapter 5)	One-way membranes	Cable mullion
	Reticulated membranes	Cable net—flat surface Cable net—anticlastic surface

- *Open System:* A structure whose primary stability is achieved only through the application of pretension forces between the structure and boundary structure anchorage, thereby creating a condition of continuous prestress in the structure

Consider a simple truss, even one with internal cable bracing. Its morphology is independent of its inclusion in an overall structural system; it is internally stable and freestanding. The cable bracing may require pretensioning, but the basic structural form is not dependent upon it. A cable truss, on the other hand, has no such inherent stability. A cable truss released from the anchoring boundary structure against which it has been pretensioned by the development of prestress loads in the tension components immediately collapses into formlessness.

Spanning Behavior

Spanning behavior is an attribute of a structural system that affects the design, engineering, and anchorage requirements for a structure, as well as the potential efficiency of a structure. Two types of spanning behavior are considered here.

Unidirectional Spanning: Systems Spanning in One Primary Direction

Planar (flat) trusses can span in only one direction, and systems built of such trusses are referred to as *one-way systems*. Morphologically flat trusses of any kind are only capable of unidirectional spanning. This is also true of mullion, glass fin, and cable mullion structures (one-way cable net).

Multidirectional Spanning: Systems Spanning in Two or More Primary Directions

Additional spanning directions increase the potential efficiency of a structure, allowing for a more uniform stress distribution. Most common are two-way systems. Orthogonal grid space frames and cable nets are examples of two-way spanning systems. Triangular grid space frames and cable nets displaying three-way spanning behavior are also conceivable. More complex geometries, as can be developed with gridshell structures, are capable of complex, highly efficient multidirectional spanning behavior along multiple load paths.

Multidirectional spanning is not simply a matter of utilizing a two-way system; it is also a function of structure configuration. A square grid octet-truss space structure, rectangular in plan, will at some point, as the plan length increases relative to the plan width, span only in the short dimension and behave as a one-way system, with little or no increase in efficiency from the other potential spanning direction. A square plan will span most efficiently, evenly distributing stresses along both spanning paths. A one-way system will generally be the most efficient solution for a rectangular facade.

Categorization by Open/Closed System and Spanning Behavior

The structure types are categorized in Table 1.3 by inherent stability (open or closed system) and spanning behavior (unidirectional and multidirectional).

TABLE 1.3 Categorization by Open/Closed System and Spanning Behavior

Closed Systems	Open Systems
Unidirectional Spanning Systems	
Mullion (strongback)	Cable truss
Glass fin	Cable mullion ¹⁹
Simple truss	
Mast truss	
Multidirectional Spanning Systems	
Space grid structures	Cable net
	Flat surface geometry
	Anticlastic surface geometry
Gridshell (triangulated or moment resistant)	Gridshell (pin-connected quadrilateral with cable bracing)
Tensegrity	
Cable-strut system (closed)	Cable-strut system (open)

Chapters 2–5 examine the structure system types categorized in Table 1.3. Readers who are intent upon exploring a particular structure type may choose to skip to the appropriate chapter. Glass and glass systems are discussed next so that the following chapters can describe the structure types within the context of these materials and systems.

