Skidmore, Owings & Merrill Foundation
2000 Mechanical/Electrical Building Systems Traveling Fellowship

Glass Enclosure Systems

Final Report
Prepared by Calvin K. Kam
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| 6. Final Statement |
The Role of Glass System in Building Systems Design

Brief Paper Intention

The intention of this brief paper as well as the proposed travel itinerary is to explore through building examples in Western Europe, the innovative incorporation of glass into building systems to promote energy efficiency and enhance the architectural perception. Both paper and proposed travel itinerary will focus on the sustainability of glass as a material for façade, curtain-wall, and roof.

The Role of Glass System in Building Design

The adoption of glass as façade, wall, or roof material offers a very architecturally powerful opportunity—transparency. Glass is also often associated with openness, natural light, and views. Such qualities of this material have earned universal reception from architects and designers, who often perceive glass as a pure form of modernity.

However, glass also has certain physical properties that require thoughtful and analytical designs to avoid resulting in adverse energy and mechanical performances. Those problems usually associate with excessive thermal gain and direct sunlight, which would cause inefficient energy consumption and create uncomfortable building environment for users. Hence, the application of a glazing system cannot be followed without truly understanding the underlying principles and implications.
The Solutions

*Brissoleil*: Brisesoleil or louver is a fixed solar shading device attached at the exterior of a building. It stops direct penetration of sun into a glass façade.

Example includes Lycee Polyvalent in France, by Norman Foster and Partners. This linear building utilizes the glazing system to maximizes views to the south and employs brisesoleil to shade direct penetration of high summer sun in the south elevation.

*Flexible Glazing*: Glass façade can be electronically or mechanically operated to allow natural ventilation in summer while retaining heat energy in winter.

Example includes Science and Technology Park in Gelsenkirchen, Germany by Kiessler + Partner. This technology center has a 3-story west-facing glass façade. The lower third can be electronically operated to allow natural ventilation.

*Double-layer façade*: Double-glazing can minimize heat gain or loss by reducing thermal transmissivity through the two glass systems and the air gap in between. In the meantime, natural light can still be let in.

Example includes the Debis Headquarter in Berlin by Renzo Piano Building Workshop. The 21-story office building in the Potsdamer Platz utilize double-layer façade for regulated natural light as well as ventilation.
Reflectivity & Electronics: Glass layers with higher degree of reflectivity can increase the thermal insulation of glass. There are also electric sensors that can respond to environmental conditions. They often utilize the air gap in a double-glazing system for regulating the level of ventilation.

Example includes Dusseldorfer Stadtto in Germany. The 16-story office building uses the space between the two skins of the façade for a high-reflection sunscreen, which is incorporated with sensors and motors that can regulate the temperature of the interior spaces electronically.

Conclusion

Brisesoleil, flexible glazing, double-layer façade, reflectivity and electronics present generalized solutions and methods to improve the environmental and mechanical performance of glass as a building material for façade and roof. Other strategies include tinted glass, cavity glass façade, water film, translucent glass, etc. I would like to take the proposed traveling opportunity to visit the diverse examples of such strategies and innovative glazing systems in Western Europe that pertain to sustainability.
1. Proposal

Brief Paper of Intent

Bibliography


These sites are selected to study the diverse ways in which building systems are integrated in architectural concepts. The notion of sustainable architecture is studied with special attention to the strategies of designing glazing systems that are energy-efficient.

Day 1 – Day 30  Germany

Site: Debis Building, Berlin  
Architect: Renzo Piano Building Workshop

Site: Offices and Housing at Potsdamer Platz, Berlin  
Architect: Richard Rogers Partnership

Site: Commerzbank Headquarters, Frankfurt  
Architect: Norman Foster and Partners

Site: Das Dusseldorfer Stadttor, Dusseldorf  
Architect: Petzinka, Pink und Partner

Site: Science and Technology Park, Gelsenkirchen  
Architect: Kiessler + Partner, Munich

Site: New German Parliament, Reichstag, Berlin  
Architect: Norman Foster and Partners
Day 1 – Day 30  Germany  (Continued)

Site: Ludwig Erhard Haus, Stock Exchange, Berlin  
Architect: Nicholas Grimshaw and Partners

Site: Library and Cultural Center, Herten  
Architect: LOG ID

Site: Hotel Kempinski, Munich Airport  
Architect: Murphy/Jahn

Site: RWE Tower, Essen  
Architect: Ingenhoven, Overdiek + Partner

Site: Leipzig Exhibition Grounds, Leipzig  
Architect: Volkwin Marg

Site: Telekom Headquarters, Bonn  
Architect: Kammerer + Belz, Kucher and Partner

Site: Thermal & Mineral Baths, Stuttgart-Bad Cannstadt  
Architect: Beck-Erlang + Partner
Day 31 – Day 37  The Netherlands

Site: Library, Delft University of Technology, Delft
Architect: Mecanoo Architekten

Site: IBN/DLO Building, Wageningen
Architect: Behnisch, Behnisch & partner

Site: VROM Offices, Haarlem
Architect: Architectenbureau ir. Rudy Uytenhaak

Day 38 – Day 40  France

Site: Lycee Polyvalent, Frejus
Architect: Norman Foster and Partners

Day 41 – Day 43  Spain

Site: Public Library, Pompeu Fabra, Barcelona
Architect: Miquel Brullet I Tenas
2. Research Studies

Glass Enclosure Systems

1) Research Intentions

This research will focus on both the sustainability and the structural reliability of glass as a “building skin” material for façade, curtain-wall or roof. The successes and problems associated with the energy and structural performance of glass will be studied, through the analyses of precedents, primarily from Western Europe. The investigation will explore the possible solutions as well as the innovative strategies that incorporate glass with building systems to promote energy efficiency and enhance architectural perception. Sustainability and structural challenges will be studied. The implications and validity of such solutions under the climatic and seismic characteristics of Southern California will be analyzed.

2) Evolution and Importance

Background of Glass—The Evolution of its Chemistry and Architectural Applications

According to Button, David, et al. (1993), glass is the oldest man-made material. Glass was discovered in Egypt around 1500 B.C. It is mainly constituted of silicon dioxide (sand) in the form of liquid solidified at room temperature. Unlike crystal, glass has an irregular molecular structure that makes it transparent, which is the most distinguishable physical property of glass. Meanwhile, glass is also inert in that it does not form any chemical compounds. Glass is an inorganic compound that is degradable therefore suitable for recycling. By adding different admixtures, the physical properties of glass can be enhanced for architectural application. Examples of such properties include porosity, weathering resistance, transmissivity, and conductivity.

Transparent glass was first used in buildings in the First Century B.C., in the Phoenician city of Sidon. Due to the constraints of load bearing wall construction, glass was mainly used as mosaics and windows until the construction of the Crystal Palace in London by Sir Joseph Paxton in 1851. The Crystal Palace was considered as a structural breakthrough of the application of glass, as it was the first use in a cast iron skeletal framing system. It used 270,000 panes of hand-blown glass dimensioned 4 feet by 10 inches. The successful completion of the Crystal Palace proved that glass was able to fill much larger window openings for more types of buildings in addition to Gothic cathedrals.

Since then, glass as an enclosure system became widely used in applications such as greenhouses, train stations, street arcades, exhibition halls, etc. The Bauhaus in Dessau by Walter Gropius in 1926 was among the pioneering examples of a glass curtain wall. The Bauhaus is a full glazed workshop. It uses a transparent building skin with the intention of integrating exterior with interior spaces. Ludwig Mies van der Rohe followed the movement of “New Building” in which light, air, and sunshine within the building were appreciated as the ideals. With the integration of an air-conditioning system, the designs of Mies van der Rohe subsequently created the prototype for fully glazed tall buildings.

The Bauhaus in Dessau, by Walter Gropius.

Until the 1970s, glass enclosure systems were criticized for being indifferent to their surroundings, orientation, climate, and geography. Their poor performance in energy efficiency prompted architects and designers to analyze glass critically during the global energy crisis. With the addition of the “Sick Building Syndrome” discovered in air-conditioning systems, the notions of sustainability and natural ventilation have...
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Architectural Application as an Enclosure System

The adoption of glass as a façade, wall, or roof material offers a very powerful architectural opportunity—transparency. Glass is also often associated with clarity, openness, natural light, and views. Ideologically, glass symbolizes purity, health and social well-being. Such qualities transform glass into a system for application, which earned universal reception from architects and designers, who often perceive glass, and its steel skeleton companion, as a combined pure form of modernity. The popularity of glass application in architecture is a result of its transparency. Functionally, glass as an enclosure system offers visual, thermal, structural, as well as mechanical opportunities for designers to explore.

Visually, the transparency of glass allows daylight into a building. Daylight, a requirement for building occupants since ancient times, can improve the quality of an interior space. Not only does daylight serve for functional illuminations such as reading, machine operation, model-making, etc., but also it creates light and shadow which work together in revealing the form and texture of any space. The other visual function of glass is view opportunities and reflection. Depending on the physical properties of glass panes in a glass enclosure system, different degrees of clear view and reflection can be provided and achieved at different ambient light levels. Thus a dynamic visual image of a façade or roof system can take place. Very often, from an exterior point of view, glass systems are dominated by reflection in the day-time and transmission of interior light in the night-time. This behavior tends to stay in the other direction if referenced to the interior perspective.

In the aspect of thermal functions, glass has the responsibility of filtering heat gain and heat loss. It has a major impact in maintaining the thermal equilibrium of the building’s interior spaces. Glass panes must structurally be durable and resistive to static, dynamic, as well as impact loads. Other mechanical function requirements of glass systems may include withstanding thermal stress, intermediate fire resistance, and sound insulation.

3. The Issues

Energy Efficiency Problems—Light, Heat Loss, Heat Gain & Thermal Balance

Glass has certain physical properties that require thoughtful design to avoid adverse energy and mechanical performance. Those problems are usually associated with excessive thermal gain and direct...
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sunlight, which cause inefficient energy consumption and create an uncomfortable building environment for users. Hence, the responsible application of a glazing system requires truly understanding the underlying principles and implications.

Daylight travels with a radiation of heat energy. The attempt to admit more daylight through a glazed space may result in solar overheating, which causes discomfort for occupants in a space. This solar overheating causes an increase in internal air temperature. In order to mitigate for human discomfort, additional energy for cooling is needed. Hence, the thermal transmissivity of glass incurs unnecessarily excessive loads on both the ventilation and air conditioning system, which contribute to an overall heating of the building. With the same principles, during winter heat from the interior space travels with long wave radiation and conduction through the glazing to the exterior. Thus, heat is lost to the environment due to temperature differential. As a result, an extra heating load is put on the building’s heating system. In both solar overheating and heat loss cases, glass enclosure systems present an energy inefficiency problem which requires additional energy to maintain the thermal balance of interior space.

Structural Challenges—Static, Dynamic, Construction Details

Structurally, glass requires high precision for construction. Since glass is usually transparent, the structure supporting it is not be hidden. As a result, glass systems often require precision as well as care in detail. Meanwhile, glass’s weak compressive strength and dynamic responses pose challenging issues for its application in a seismic active region such as southern California.

Similar to other building materials such as steel and concrete, glass deforms under stress. Its rate of deformation is directly proportional to the magnitude of the applied stress. Hence, glass demonstrates a linear stress-strain relationship. This perfectly linear relationship holds until the glass reaches its maximum capacity when further stress causes the failure of the glass. The failure of glass is instantaneous. The brittle quality of glass offers no yielding or further plastic deformation before failure. This property of glass poses a very challenging issue regarding the reliability of glass as a structural material.

Since glass surfaces may contain flaws and cracks, the brittle property of glass makes those defective local areas vulnerable of local stress concentrations. Once the glass cannot withstand the accumulation of local stress, failure in the form of cracking will occur. Hence the erection of a glass enclosure system relies upon the strength of its supporting secondary structural system. The choice of a supporting structural system would have direct implications on the complexity and cost of the fixings and detailing of the glazing system.

Other Problems Associated with the use of Glass Systems—Glare, Fading

Glare occurs when glass systems allow excessive illumination that creates contrasting discomfort for a human eye. The measure of excessiveness, discomfort, as well as the response subjectively varies from person to person. On the other hand, the heat and light transmitted through glass may induce a chemical decay on dyes and pigments whose process is known as fading. Although there are glare, fading, as well as other problems associated with the use of glass systems, the scope of this research paper is to focus on the solutions that pertain to energy efficiency problems and structural challenges.

4) The Solutions

The Philosophy and Physics Behind the Solutions

The various solutions for visual, mechanical, and structural problematic issues associated with glass can be divided into two categories: direct solutions and indirect solutions. Direct and indirect solutions may be used separately or concurrently to respond to the problems caused by conventional clear glass.

Direct solutions take an active modification to enhance the physical properties of glass such as reflectivity, transmissivity, and absorption. These solutions either apply body tints or coatings through laminations onto glass surfaces or manufacture of a performance-specific glass through chemical admixtures
to achieve certain property levels.

On the other hand, indirect solutions utilize systems or assemblies that are external, in-between, or internal of glass enclosure systems. Louvers, blinds, air gaps, and electronic devices are examples of indirect solutions. Meanwhile, through fundamental design solutions such as orientation, tilting angle, or window areas, designers can often substantially solve or alleviate the energy or structural problems.

Fundamental Design Solutions

With critical reasoning and an understanding of the physics of mechanical and structural systems, architects and building designers can often avoid the needs of meticulous detailing and redundant systems. The awareness of specific geographical and climatic settings of each design project play an important role in fundamental design solutions, as latitude, prevailing wind directions, humidity, etc. could all support or diminish logics for the use of glass. In some cases, rather than designing for a double layer façade that requires extra materials and labor to achieve solar control purposes, architects can design some programmatic zones or functional necessities as solar filtering means. In dealing with a fully-glazed design decision in the Center Pompidou, Renzo Piano and Richard Rogers utilized all the necessities of a building system—circulation and structural skeleton—for solar shading. In the meantime, the configuration also allowed the expression of the building’s mechanical factory character.

The Solutions to Direct Light—Principles, Conventional Solutions

With careful design and integration, glass can save a significant quantity of electrical energy by reducing the need for artificial lighting. However, direct sunlight, excessively bright diffuse light, and light that could create discomfort. Solutions to filter the excessive light usually involve louver systems. A “brissoleil” or louver is a fixed solar shading device attached at the exterior of a building. It stops direct penetration of sun into a glass façade. Examples include the Lyceée Polyvalent in France, by Norman Foster and Partners. This linear building utilizes the glazing system to maximize views to the south and employs a brissoleil to shade direct penetration of high summer sun in the south elevation.
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The Solutions to Heating & Cooling—Principles, Conventional Solutions

Double skin façades with flexible glazing can minimize excessive heat gain and loss issues, while inducing the opportunities of natural ventilation.

A double-skin façade creates a buffer zone, also known as a cavity, between the interior and exterior through the erection of two building skins. It employs two layers of glass as building skins of the façade and therefore is also called double-glazing façade. The buffer zone allows fresh ambient air to enter the façade cavity for natural ventilation. Air can be filtered for admission into the interior spaces. In the same way, heated air from the interior space can also be expelled through openings or vents at the top of the cycle. Hence, a loop of convection is produced for natural ventilation in the summer. In winter, internally heated air can be retained through either closing the vents or maintaining an insulating air gap in the buffer zone. As a result, double-glazing can minimize heat gain or loss by reducing thermal transmissivity through the two glass systems and the air gap in between. Natural light can still be let in.

Example of double-glazing includes the Devis Headquarters in Berlin by Renzo Piano Building

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Workshop. The 21-story office building in the Potsdamer Platz utilizes double-layer façade for regulated natural light as well as ventilation.

In Flexible Glazing, the glass façade can be electronically or mechanically operated to allow natural ventilation in summer while retaining heat energy in winter. An example is the Science and Technology Park in Gelsenkirchen, Germany by Kiessler + Partner. This technology center has a 3-story west-facing glass façade. The lower third can be electronically operated to allow natural ventilation.

Ecological, Hybrid & Innovative Solutions

Plantations and water films are natural elements
2. Research Studies

Glass Enclosure Systems

that can improve the thermal and acoustic insulation of a glazing system. With proper plantations within glazed buildings, the oxygen level in the air can be increased. While glass transparency provides natural light needed by the plants, vegetation offers shade and humidity to the interior space in return. It can humidify internal air by transpiration, which helps the cooling of the interior space. The Commerzbank Headquarter in Frankfurt by Foster and Partners incorporates a spiral subtraction of office space for plantation with the intention to improve the visual quality of an office space. On the
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On the other hand, the British Pavilion in Seville by Nicholas Grimshaw and Partners used a water film to serve as an insulating layer which also added a dynamic translucency to the appearance of the façade.

Current innovative solutions involve the use of electronics and micro-processors to adjust glass properties such as reflectivity and transmissivity. Glass layers with higher degrees of reflectivity can increase the thermal insulation of glass. There are also electric sensors that can respond to environmental conditions. They often utilize the air gap in a double-glazing system for regulating the level of ventilation. An example includes the Dusseldorfer Stadtitor in Germany. This 16-story office building uses the space between the two skins of the façade for a high-reflective sunscreen, which

Das Düsseldorfer Stadtitor in Düsseldorf, Germany.
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Glass Support Systems

Glass must always be separated from contacting any metal due to its brittle and local overstressing nature. There must always be a soft interface that directly contacts glass to absorb the stress encountered by the latter. Such soft interfaces usually are a silicone building sealant or in some cases, a structural sealant that can serve as a glass supporting structural system of its own. Framed systems, suspended assemblies, countersunk bolt fixing, and
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Glass Enclosure Systems

Three primary types of glass enclosures are:

1. Frameless glass systems
2. Structural glass systems
3. Curtain wall systems

Frameless glass systems are defined by their use of glass panes with minimal structural support, allowing for large and seamless views.

Structural glass systems, on the other hand, utilize structural elements to support the glass, ensuring stability and safety.

Curtain wall systems combine elements of both frameless and structural glass to create flexible, aesthetic structures.

These systems are characterized by their ability to enhance natural lighting and provide a seamless integration with the environment.

The selection of a particular system often depends on factors such as aesthetic requirements, structural considerations, and environmental impact.
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planar glass façade system in the British Pavilion at Barcelona Exhibition, while Goldstein Ween also employed a clear single glazed planar system for the Lots Road project in London, United Kingdom.

From Buiton, David, et. al. (1993), structural sealant glazing, also known as stuck-back systems, involve glass panes bonded into a frame using structural silicone sealant. No external cover beads are present. The structural performance of the system relies on the bonding quality, as well as the adhesion and cohesion of the structural sealant, rather than the strength of the bolts as in the cases of planar systems or suspended assemblies. Hence, the structural sealants are designed to withstand the severe stresses resulting from dynamic and static loads. As in all previous examples, the structural sealants are designed so that no twisting or bending stress would be transmitted to the glass edges and the glass panes. Foster and Partners’ Cambridge Faculty of Law employs a structurally sealed double glazed system that curved in a cylindrical shell.

The Solutions to Dynamic Challenges

Earthquake, thermal expansion or contraction, snow, and wind pose dynamic challenges to glass enclosure systems. Solutions to dynamic loads usually combine the application of glass types with the design of supporting structural systems.

The brittle fracture risk of glass can be alleviated through the use of laminated safety glass. The physics of such glass is very similar to the case of reinforced
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cement, in which reinforcing steel bars are embedded in concrete to enhance its ductility and to avoid its sudden brittle failure. Laminated glass bonds two or more panes of glass together with an interlay of a plastic material such as resin. It can also incorporate other admixtures to achieve specific mechanical and structural performance standards. On the other hand, wired glass employs a steel wire mesh between two separate ribbons of rolled glass. Toughened glass, also known as tempered glass, is treated with extreme heating and rapid cooling to achieve a high compressive strength that is four to five times as strong as normal glass.

Laminated, wired and toughened glass ensures the glass possesses residual load-bearing capacity during failure. Upon failure, the glass fractures into small harmless dices rather than scattered into totally fragmented pieces. Hence a lot of stress or energy can be dissipated to avoid their emission in sudden or harmful ways.

According to Krewinkel (1998), each glass enclosure system and its supporting structural system is required to accommodate movement arising from dead load deformation, thermal expansion, dynamic load deformation, as well as impact load deformation. Due to the brittle and inelastic nature of glass, either the sealant joints in between glass panes or the supporting structural systems would bear all the responsibility for movement and deformation allowance. The former usually utilizes pane-to-pane joints to withstand smaller magnitude of deformation through the compressibility of the sealant material. Meanwhile, the latter would integrate sliding or pivoting fixings with the supporting systems to allow greater magnitude of movement. In either cases, the objective is to transfer away from the glass panes any movement or local overstressing encountered by the system.

In bolt and plate systems, lateral loads can be resisted through stiffening the suspended glazing system by means of toughened glass stabilizers. Those stabilizers are applied at each vertical joint of the glazing system to enhance the stiffness of the façade. The façade is hung at the top edge through hangers and bolts, and is sealed in the peripheral channels. The system acts as if the façade is floating or hanging, hence, the issues of differential movement, caused from dynamic load or thermal stress, among the components can be avoided. As a result, the whole façade can be treated as a rigid body in design for dynamic loads. The façade can be seen as a whole system with the vulnerability of its parts, consisting of glass panes and sealants, being taken care of by the bolts and plates.

The Waterloo International Rail Terminal by Nicholas Grimshaw and Partners shows how glass enclosure systems deal with the dynamic challenges. The dynamic loads include the forces imposed by the 800-seat trains arriving and departing the station, thermal displacement, the subsidence of the platform, the
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deflection of the rail bed when trains arrived, etc. Hence, part of the glazing system utilizes overlapping panes of glass in aluminum frames. The frames are suspended from the structure. The advantage of using an overlapping pane system is to facilitate the curvature as well as to allow for movement. The structure is hinge-joints to form a three-pin arch which ensures no bending moment at the pin points, which also increases the flexibility and dissipation of stresses within the glass enclosure system.

The Innovative Solutions

Bixler, David, et al. (1993) concluded that the automobile industry had been a pioneer in conducting glass research because of the competitiveness and demand for innovative design from its market. Their research on variable transmission glass could greatly increase the efficiency for buildings. The concept of variable transmission glass transforms the conventional fixed performance glass into a range of dynamic characters. An intelligent light and energy management system will evaluate all internal and external variables to alter the transmissivity, conductivity, and other physical properties of the glass in response to the environment. Electrochromic, photochromic, thermochromic, and electroluminescent glass are areas of such new research activities. In electrochromic glass, heat and light transmissivity of the glass can be varied by electrical signal. An electronic voltage reduces solar radiation transmittance through posting a certain color with a specific transmissivity. On the other hand, electroluminescent glass utilizes electroluminescent display technology to display information or simple color patterns, integrating decoration with communications and technology.

5) Implications and Validity

Implications of Energy Efficiency Problems & Structural Challenges

Architects and building system designers should be critical in judging the validity of glass enclosure systems. The inherent mechanical and thermal problems associated with clear glass, as experienced by earlier glass enclosure designs such as the Bauhaus or the office prototypes by Mies van der Rohe are convincing that energy efficiency must be put into account when designing with glass. With the vivid crisis of global energy in the 1970s, designing with sustainability has become a necessity in glass enclosure systems.

Although various solar-control, double-skin, ecological, and electronic systems provide theoretical promises to solving the inherent problems associated with glass enclosure systems as presented previously, there are still many practical issues and maintenance problems that architects face. In terms of cost, dynamic facades are expensive to operate, while double-glazing is even more expensive than most cladding systems. Hence, do the “energy-saving” systems deserve the amount of extra construction and manufacturing energy to spend in the first place? Very often, buildings employing another set of enclosure systems with careful design attention can be equally as sustainable as one with a glass enclosure system. In those cases, the extra energy for new construction of glass systems, and the continuing extra energy spent on maintaining the systems will discredit all the claims of glass systems. Therefore, detailed planning, estimates, and projection should be studied by designers adopting a glass enclosure system. They should also weigh and consider alternative building systems, since with good design consciousness, other building systems can also enjoy a sustainable building life as efficient as glass systems.

Glass enclosure systems are more expensive and energy-inefficient to build and maintain. On the other hand, they provide architecturally sound opportunities for appearance, light, perception, view, etc. Ultimately, it is a collaborative judgment call of value and intention by the designers, with their clients, the users, and other important groups.

For all glass solutions in structural supporting systems or production of modified glass, the fundamental weakness and structural property of glass is still unaltered. The solutions are passive in that they either transfer all the dynamic, tensile, and bending stresses away from the system, or rely on a secondary system, such as bolts and plates, to withstand those forces. The underlying property of glass being brittle, can only be alleviated upon failure, with a minor allowance of plastic behavior. Yet, glass panes are still not able to withstand any forces other than pure compression. With a good degree of safety factor for expansion and contraction, glass can stand structurally with good reliability in regions where all the dynamic loads are within predictable. However, for active seismic regions, the displacements,
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Validity of Solutions in Southern California

Most building examples and literature to which this paper is referenced are taken from Western Europe. Client demands, government regulations, local architectural practice and trends may all result in encouragement of adopting glass enclosure systems. The higher energy cost and the impact from the 1970s energy crisis have seeded the notion of sustainability in Northern and Western European countries such as Finland, Germany, France, the Netherlands, the United Kingdom, etc.

During an interview, I briefed Professor Marc Schiler about my findings about glass enclosure systems. He agreed that European countries are more advanced in the investigation of the sustainability of glass. He believed that the reasons are due to two main factors. The first factor being the strong consciousness induced by the Green Party, a political group that advocates sensitivities towards energy issues, while the second factor was caused by the intentions and commitments of the local clients and architects to design buildings that are able to last for longer term. As a note, Professor Schiler pointed out that such demands had induced even Richard Meier and Partners, a firm which was persistent in the adoption of universal building materials and designs, to set up a department which dealt with energy and sustainability in their European office.

Meanwhile, any trend of extensive use or exploration of glass enclosure systems has not been observed in Southern California. The unique local climate with abundant sunshine, low humidity, and minimal precipitation all tends to disqualify the investigation or incentives to solve the inherent mechanical problems associated with glass enclosure systems. Meanwhile, the lower energy cost, more relaxed regulation, and local trends in Southern California also make the local consciousness of sustainability relatively behind that of many Northern or Western European countries. When asked about the validity of glass enclosure systems in Southern California, Professor Schiler believed that if designed correctly, glass systems would work and were capable of offering excellent natural ventilation by convection. He quoted Philip Johnson’s Crystal Cathedral in the Orange County to show its highly reflective glass, low transmissivity, and high internal space had formed a good example, among very few other precedents in the local region.

Professor Jeff Guh emphasized that glass had absolutely no capabilities to withstand earthquake forces. Glazing must rely on secondary supports for movement allowance. In my opinion, such systems would be much more successful and reliable in regions where the dynamic displacement range is within prediction, while their validity in a seismic-active region would diminish as earthquake actions are unpredictable. With the fact that most glass does not yield upon failure, to design a good glass enclosure system would take a much higher factor of safety to ensure its reliability.

6. Conclusion

The discovery of glass through artificial chemical process had a huge impact on human kind. Among the vast variety of functions of glass is its usage in building material. Since Paxton’s Crystal Palace in the mid 19th century, glass became more widely used in cladding for facades and roofs, and as an integral option for building enclosure systems. Transparency is the unique property that makes glass different, attractive and sometimes superior to other building materials. Transparency allows view in and view out of an enclosed space, offering a naturally interactive opportunities on which architects and designers can build complexity. Glass enclosure systems can also both transmit and reflect light. It conducts heat and allows long wave radiation of heat energy. It offers the advantage of insulation, filter, and can be resistant to sound and impacts. Yet, it also tends to degrade the thermal balance of the interior space with its higher transmissivity. Meanwhile, it is a brittle material that is dangerous in tension and disastrous in failure. Glass system’s natural performance in both energy and structural aspects pose challenges for an efficient adoption.

With careful attention paid towards fundamental design elements such as climate, solar orientation, section, openings, etc., many adverse effects of glass systems can be alleviated. Louver systems, double-glazing, movable glazing, and ecological plantations or water films are examples of additional...
configurations that can filter the amount of light admission, and avoid excessive heat gain or heat loss. These systems are indirect solutions that are add-ons to the glass systems. For direct solutions, the basic properties of glass in a system are modified to achieve specific standards. Fundamental design, indirect, as well as direct solutions can be act together in synergy to promote the efficiency and performance of glass enclosure systems. Although such solutions offer promising responses to the environment and energy consumption, the initial construction and subsequent maintenance of glass enclosure systems do not. Hence, designers are encouraged to consider alternative building systems with equal care in sustainable design. With that, they can cooperate with the owners and clients to determine the most efficient systems that meet their requirements. The intention is to avoid thoughtless usage of glass enclosure system without exploring other equally plausible systems that take less energy to build and to maintain.

Structurally, glass can be supported by a conventional framed system, suspended assembly (bolt and plate system), countersunk bolt fixing (planar system), as well as structural sealant. The concept between all four supporting systems is virtually the same—to withstand or transfer away the stresses incurred by static, dynamic, or impact load, and ensuring that the glass panes are not subjected to any tensile, twisting, bending, or overturning stresses, but only pure compression. Local overstressing must be alleviated or avoided. Hence, the support systems also need to encounter and allow any movement in the form of expansion, contraction, or unpredictable forces such as seismic displacements. Meanwhile, the manufacture of glass can also ease the responsibilities of the supporting systems through incorporating laminated, wire, and toughened glass panes. Such modified glasses have the advantage of withstanding a higher compressive strength, and possessing plastic behavior during failure. However, the fundamental susceptibility of glass of being brittle and compressive still remain.

With the energy and structural challenges associated with glass enclosure systems presented in this essay, it can be concluded that if designers were to employ a glass enclosure system in Southern California, logical reasoning for such an adoption is necessary to demonstrate advantages over other sustainable building systems. Such logical reasoning may include a preference for designs that could only be materialized through the use of glass systems. If this decision is made, then designers should carefully look into both mechanical and structural performances of the systems. While fundamental design, indirect, and direct mechanical solutions can fine-tune the lighting, heating, cooling, and visual qualities of the interior space, the careful structural design for a glass enclosure system in respect to static, dynamic, and impact load will ensure its occupants are safe, the structure will last, and set another sustainable and strong precedent for the local region.

7 Bibliography


3. Travel Itinerary

Dates, Cities & Sites

May 29 – June 7

London, United Kingdom
Waterloo International Rail Terminal
Waterloo Imax Theater
Lloyds Building of London
Millennium Dome
Stansted Airport

Cambridge, United Kingdom
Cambridge Faculty of Law
Cambridge Faculty of History

June 7 – June 13

Paris, France
Colines Le Defense
Center George Pompidou
Grand Louvre
TGV Station, Charles De Gaulle Airport
Museum of Science & Industry
Institute de Arab
National Library
3. Travel Itinerary

Dates, Cities & Sites

June 13 – June 18

Rotterdam, The Netherlands
  Netherlands Architecture Institute
  Rotterdam Cinema Complex
  Cube Housing
  Erasmus Bridge

Delft, The Netherlands
  Central Library, Delft University of Technology
  Aula Congress

Amsterdam, The Netherlands
  National Academy of Film and Television
  Amsterdam International Terminal
    (Under Construction)
  Museum of Science and Technology

June 18 – June 22

Dusseldorf, Germany
  Des Stadttor
  UFA Palast
  Medienzentrum Zollhof
3. Travel Itinerary

Dates, Cities & Sites

June 18 – June 22 (Continued)

Gelsenkirchen, Germany
Science and Technology Center

Essen, Germany
RWE Tower

June 22 – July 2

Berlin, Germany

Potsdamer Platz
Info Box
Arkade
Imax Theater
Sony Center
Debis Site
Reichstag
Jewish Museum
New National Gallery
Alexander Platz
Bauhaus Archiv
Kaiser William Church
Pergamon Museum
The Dom
Altes Muesum
Ludwig Erhard Haus
Gallery Lafayette
FriedrichstadtPassagen Quartier 206
3. Travel Itinerary

Dates, Cities & Sites

June 22 – July 2 (Continued)

Hannover, Germany
Hannover Expo 2000

Hamburg, Germany

July 2 – July 12

Leipzig, Germany
Leipzig Messe (Exhibition Hall)

Dresden, Germany

Frankfurt, Germany
Commerzbank

Stuttgart, Germany
Bad Cannstatt Mineral Spa
SI Centrum
Exhibition Pavilion, Haus des Waldes
Weissenhof Siedlung
Stuttgart Flughaven (Airport)
Gottlieb-Daimler-Stadion Stuttgart
3. Travel Itinerary

Dates, Cities & Sites

July 2 – July 12  (Continued)

Munich, Germany
Olympic Park, Stadium
Dachau Concentration Camp
Munich Airport Center
Kempenski Hotel Munich

July 12 – July 14

Lyon, France
International School in Lyon

July 14 – July 18

Barcelona, Spain
Plaza Reil
La Rambla
Barcelona Museum of Contemporary Arts
German Pavilion, 1929 Barcelona Int'l Exhibition
Olympic Stadium, Telecommunication Tower & Arena
Gaudi Casa Batllo
La Pedrera (Casa Mila)
Sagrada Familia
Olympic Village
3. Travel Itinerary

Dates, Cities & Sites

July 14 – July 18 (Continued)

Valencia, Spain
Valencia Alameda Bridge and Station
Calatrava Building Sites, Valencia

July 18 – July 24

Bilbao, Spain
Guggenheim Museum Bilbao
Pedestrian Bridge by Calatrava
San Sebastian, Spain
Kursaal Auditorium and Convention Center

Madrid, Spain
Catalana Occidente

Seville, Spain
Citidal
Minerat Giralda
Alcarssa
Espanya
Digital-Photo Archive

In the accompanied compact-disc, I have organized the digital images I took from the trip into 6 slide-shows:

1) United Kingdom
2) France
3) The Netherlands
4) Berlin, Germany
5) Other Cities in Germany
6) Spain

Directions

1) Double click on the links in the root directory to launch the slide show program.
2) Single click the left mouse button on to view the next slide.
3) Right click for more options.
4) Press escape key to quit the program.
4. Documents of Studies

Sketches
4. Documents of Studies

Sketches
4. Documents of Studies

Sketches
4. Documents of Studies

Sketches
4. Documents of Studies
Sketches

SOM Foundation 2000 Mechanical/Electrical Traveling Fellowship Final Report Calvin Kam
4. Documents of Studies

Sketches
The green autograph by Renzo Piano was signed on June 23, 2000. I attended the “Conversation With Renzo Piano” lecture at the New National Gallery in Berlin.
4. Documents of Studies

Notes
Through configuration and assembly of framing members and supporting structures, glass buildings can formulate different shapes and building forms.

The Faculty of Law in Cambridge, United Kingdom (Left) used a triangulated structural silicon supporting system to form a cylindrical glass building.

Other precedent examples include a glass dome in the renovated Reichstag in Berlin, Germany (Middle) as well as an interior circular glass pyramid in the atrium of Gallery Lafayette, also in Berlin, Germany (Right).
From the building sites that I visited, glass systems were used for a great variety of functions:

**Façade:** The Des Stadttor office tower in Dusseldorf, Germany (Below) employed a fully glazed façade.
Function (Continued)

Roof: Glass-enclosing roofs are plausible for their introduction of natural light but are susceptible for undesirable thermal energy transfers. When I visited the Grand Louvre in Paris, France (Right), the entry atrium was very well lit but the entry level in the ground was very hot, in spite of the air-conditioning mitigation. Meanwhile, the glazed roof in the Potsdamer Platz Arkade in Berlin, Germany (Left) was equipped with an “intelligent system” (Please refer to “Mechanical Systems” section).
Enclosure: In the case of Waterloo International Rail Terminal, in London, United Kingdom (Below), the distinction of façade and roof was not distinctive. The enclosure of the terminal was formed by two arches. The arch with the shorter span was fully glazed as it maximized the introduction of daylight in the tight industrial site.
Function (Continued)

Floor: In Stansted Airport, London (Left), glass blocks were used in the floor of the main level to introduce natural light to the arrival terminal in the lower level.

Partition: Glass units formed in modular patterns for non-structural interior partition in the Sheraton Hotel offices at the TGV Station, in Paris Charles De Gaulle Airport (Right). With adjustable blinds, the partitions offer the occupants the discretion of transparency and light admission through their partition.
Function (Continued)

**Unconventional Façade Material:** In the Netherland Film and Television Academy, Amsterdam, The Netherlands (Belows), glass panes were used in an unconventional fashion: transparent glass panes were installed in front of a solid concrete wall, and they are not sealed or air tight. Hence, the glass did not contribute to transparency, view, nor thermal insulation, rather, they form a pattern façade material.
Mark of Entry: The Guggenheim Museum in Bilbao, Spain (Left) marked the entrance and the atrium space with a glass enclosure system. It served as the anchorage of the exhibition elements. Meanwhile, Glass canopy is also used to notate main entrance in an office building in London (Right).
5. Assessment & Visual Records

Function (Continued)

Mark of Entry: In the Palace of Louvre, Paris (Below), a glass pyramid was constructed to mark the new official entrance of the palace, forming a purely authoritative, but subtle and harmonious presence within a rich context.
5. Assessment & Visual Records

Transparency

The German Pavilion in the 1928 Barcelona Expo, Spain (Left) utilized planar elements to form pure geometric architectural elements in which water and glass offered transparency. In the Museum of Science & Industry in Paris, France (Right), glass pavilions were constructed with maximum transparency through the “frog” glass structural support system that was first ever employed.
Transparency (Continued)

The Messe (Exhibition Hall) in Leipzig, Germany (Below) had the concept of maximizing transparency to admit the maximum amount of daylight, and offers unobstructed view to the exhibition area. I was very impressed by the introduction of daylight and the successful coordination of natural ventilation.
Light

Transmission: The glass blocks of Kaiser Church in Berlin, Germany (Below) transformed and filtered light to provide a unique interior quality of light in the chapel. Such quality of light would be difficult to visualize or imagine from the exterior appearance of the glass blocks and the framing members.
Light (Continued)

Regulating: The Institute de Monde Arabe in Paris, France (Belows) had an array of mechanical regulating motif that could adjust the amount of light allowed to the building. The operation of each panel could be adjusted by the occupant as the photo in the right shows the closing of a motif.
Light (Continued)

Shading: The Imax Theater in the Potsdamer Platz in Berlin, Germany (Left) has a glass façade equipped with electrical canvas shading devices (Right) to provide shading for its inner circulation ramps.
5. Assessment & Visual Records

**Form**

**Function**

**Transparency**

**Light**

**Structure**

**Mechanical Systems**

**Maintenance & Durability**

**Social & Cultural Issues**

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**Structure**

The structural system of Grand Louvre pyramid in Paris (Below) was composed of tension cables and suspended compression structs made of stainless steel rods. The structural system appeared to be a light structure, which enhances a higher degree of transparency.
Constructed in 1980, the Museum of Science and Industry in Paris, France (Below) employed an influential structural support system for its four glass pavilions (Serre). Arrays of glass panes were suspended from top and were braced with by tensile tie rods and compressive steel tubes, braced by intermediate struts. The vertical loads were transferred through a spring to the structural steel tubes while lateral loads were resisted by the truss. Such efforts allowed pane-to-pane connection without solid structural mullions.
Structure (Continued)

The principle of glass supporting system was to ensure that no rotation moment and minimal compressive force would be transferred to a glass pane. Hence, modern systems usually employ glass stiffeners (Right) or tensile cables (Left) to resist the lateral loads and to stiffen the glass systems. The connection in the Kempinski Hotel in Munich, Germany (Left) was a point-fixed connection without full perforation through the pane. The connections in the following page were taken from the Leipzig Exhibition Hall (Messe) in Leipzig, Germany.
5. Assessment & Visual Records

- Form
- Function
- Transparency
- Light
- Structure
- Mechanical Systems
- Maintenance & Durability
- Social & Cultural Issues
Mechanical System

The Potsdamer Platz Arkade in Berlin, Germany (Left) was a shopping arcade with a main circulation “street” enclosed with a glass assembly. It incorporated mechanical devices that could swing open and close to allow natural ventilation when desired. This was also known as an “intelligent system”.

5. Assessment & Visual Records

**Mechanical System**

Such “intelligent” components were also present in the end glass walls (Below). The system relied on mechanical rotors and wheels to pull the glass panes to a 90-degree position. They acted as an remote control automatic window. The system hence could respond to the dynamic environment and could regulate the thermal barrier between the interior and the atmosphere.
Mechanical System  (Continued)

The office tower of Des Stadttor in Stuttgart, Germany (Below) had a central atrium space. The atrium was fully glazed and natural ventilation in the form of convection was allowed through the mechanical glass units in the bottom and the top of the glass facades. Such pair of mechanical glass systems would open in the summer to allow warmer air to escape in the top and to attract cooler air in the bottom. Hence, the induced thermal load on the cooling mechanical system of the building would be reduced.
The Lloyd’s Building of London, United Kingdom (Below) had its HVAC distribution and return systems expressed in its exterior façade. Since the glazed façade played a crucial role in defining thermal transmissivity, the HVAC system usually had outlets designed around the façade to provide maximum effects and control.
5. Assessment & Visual Records

Mechanical System (Continued)

During my visit to the Bad Cannstatt Mineral Spa in Stuttgart, Germany (Below), I had an interview with the facility manager of spa. The main pool of the spa was fully glazed in its walls and roof. Although the glass panes were of very high insulating value, the facility manager pointed out that during cold weather in the winter times, the main pool with glass enclosure would freeze while other pools without glass enclosure could still operate. Hence this illustrates that glass systems, particularly glass roof, would be less appropriate in cold regions where restraining heat loss would be a high priority.
Maintenance & Durability

Glass fails in a brittle and irrecoverable mode. Unlike steel which demonstrates strain hardening and ductile behavior, glass fails suddenly when it is overstressed. Safety glass or tempered glass only ensure glass to fail in a confined fashion. They don’t avoid permanent cracks. Once cracks are present, the glass panes no longer sustain their original appearance. In the case of Hotel Kempinski in Munich, Germany (Below) the cracked panes were left in place during my visit.
5. Assessment & Visual Records

- Form
- Function
- Transparency
- Light
- Structure
- Mechanical Systems
- Maintenance & Durability
- Social & Cultural Issues

**Maintenance & Durability (Continued)**

In Colines Le Defense, Paris (Belows), the cracked glass pane was removed from the façade, whose void was temporarily covered by plywood boards.
Social & Cultural Issues

Glass buildings symbolize modernity in our current world. During my traveling studies, I found it very interesting to contrast the reception of glass buildings in an urban setting.

The modern glass buildings in Cambridge, United Kingdom (Left) were situated in the southwest outskirt of the main campus. They were situated within their own cluster so as not to compete or distract with the harmoniously set Kings College, Trinity College, etc. in the main campus.
Similarly, the new financial city of Le Defense in Paris, France (Previous Right) comprised of new buildings which employed glass extensively. As in Cambridge campus, such city was avoided within the inner ring of Paris city.

Whereas in former East German city of Leipzig, Germany (Below), the government did not hesitate to replace the old exhibition hall with a new glass hall. Rather than being excluded from the main stream, the new Messe in Leipzig served as the center of the exhibition fair.
Social & Cultural Issues (Continued)

The Potsdamer Platz in Berlin, Germany was an abandoned boundary district prior to German reunification. The revival featured the Daimler-Chrysler Headquarters and entertainment facilities (Design led by Renzo Piano) as well as the Sony Center (Design led by Helmut Jahn). The Sony Center (Below and Next Page) symbolized the next generation hub with its mixed-use glass buildings. My criticism is that with the homogeneous material and subtle variations, the identities of living, working, and entertaining have been lost.
5. Assessment & Visual Records

- Form
- Function
- Transparency
- Light
- Structure
- Mechanical Systems
- Maintenance & Durability
- Social & Cultural Issues
I am sincerely grateful to the SOM Foundation for sponsoring and organizing the Traveling Fellowships. My two-month traveling in five western European countries and about 20 different cities has tremendously enlightened and inspired me in design, construction, and beyond.

Having studied “Glass Enclosure Systems” through independent research and subsequently being able to physically visit all the building sites was like switching from a static learning mode to a dynamic learning mode. Through traveling, I was finally able to fully understand the context of each site, to feel the scale of the construction, to experience the spatial sequence, to interact with the occupants, and to observe the dynamic responses of the buildings or infrastructures in which I had been studying.

I found that articles or books would only show the best “camera shots” of a system or a building. Such representations were often illusive to one’s perception. Even with text, diagrams, or other supplementation, the images might not be the best description of the wholeness or the reality.

Not only had my traveling studies reinforced my initial understanding of glass enclosure systems, but it also induced me to evaluate their designs and applications in new and different ways. From the building sites I visited during the trip, I was able reaffirm and expand my understanding of glass with respect to Form, Function, Transparency, Light, Structure, and Mechanical Systems. I was particularly interested in intelligent glass systems which would improve their energy efficiency through dynamic responses to changing environments (e.g. Das Stadtor, Arkade).
Meanwhile, my views towards durability, maintenance, and identity of glass enclosure systems had developed substantially throughout the course of my traveling, as I discussed in the previous section.

Our society currently would receive glass systems as component of modernity. However, from my comparison of buildings using different materials during the trip, I thought that the durability and abrasion resistance of glass were not comparable to other building materials such as stones, concrete, steel, plaster, or wood. Any local failure in a small area of a glass would impact the overall appearance and further capacity of the glass pane or system as a whole. Moreover, once a crack occurs, the glass pane would be in an irreversible failure mode.

Buildings from Classical, Renaissance, and Baroque period are still standing and conveying their original statement after centuries and centuries of testing. With a brittle character and an irreversible failure mode, how long will glass enclosure systems be able to maintain its original integrity?

My traveling experiences had reinforced myself with the concept that there were admirable differences and distinctions in the materiality, form, structure of public buildings versus private buildings, residential buildings versus office buildings, and so on. Such differences in precedent building examples were driven by reasons and cultures from the occupants and the contexts. Hence, I would criticize the homogenous application of glass enclosure systems that diluted functional and civic identities, and abstracted the meaning of architecture and urban planning.
My traveling studies took part in an important milestone of my life. It was right after the completion of my undergraduate studies from the University of Southern California (USC), where I double majored in Architecture and Civil Engineering. I felt that through visiting all the pre-selected and impromptu sites, my traveling experiences bonded and synergized my understanding in the design, sciences, and social implications of building construction.

Currently, I am pursuing a Master of Science degree in Design and Construction Integration at Stanford University. The critical analysis, independent observation, and qualitative assessment skills that I developed from my traveling fellowship are valuable to my current study and future career pursuit.

I am thankful to Professor Henry Koffman (USC) for recommending me to the SOM Traveling Fellowship, Professor Robert Harris (USC) and Professor Douglas Noble (USC) for research guidance, as well as Lisa Westerfield, Chris Sullivan, Peter Land, Raymond Clark, and Craig Hartman (SOM Foundation) for their valuable advice and supports.

Calvin Kam
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