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Curtain Wall Systems

A Primer

Committee on Curtain Wall Systems

ASCE

EDITED BY
Ali M. Memari, Ph.D., P.E.

AEI ARCHITECTURAL ENGINEERING INSTITUTE

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Prepared by
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PREFACE

As the trend in building envelope system design moves toward significantly more transparent elements instead of opaque systems, the role of architectural glass is becoming more important than it once was in traditional window and curtain wall systems. Expectations of today's curtain walls that use architectural glass or other glazing products exceed the basic functions of providing natural lighting and protecting the interior from environmental effects such as wind and rain. Curtain wall systems are now expected to conserve energy, provide occupant comfort by controlling heat flow and solar radiation, and, in some cases, even convert solar energy to electricity. Last but not least, curtain wall systems are expected to perform acceptably when exposed to natural disasters such as hurricanes, earthquakes, and man-made hazards such as explosions and blasts. As these functions imply, depending on the application, proper design, fabrication, construction, and maintenance of advanced and efficient curtain wall systems demand involvement of professionals from several fields of engineering and building technology.

Design of building envelope systems in general and curtain wall systems in particular is not part of the curricula in architecture, architectural engineering, and civil engineering programs. The professionals whose work involves design, fabrication, and construction of such systems likely receive their training on the job and learn the fundamentals and design principles through experience of working on various projects. Few books and guidelines specifically address most major aspects of interest in glass curtain wall systems. The main goal of this book is to provide one such reference for beginners with no prior knowledge of curtain wall systems. The book is considered a primer because it does not treat the various subjects discussed at great depth. This book's chapters provide an introduction to several topics related to curtain wall and glazing systems, including material properties; manufacture, fabrication, and construction methods; various loading types and testing methods; design methodologies with respect to wind, seismic, and blast; building physics with respect to waterproofing and energy efficiency; and some technological innovations and new developments in glazing systems and design, and construction of complex forms.

This book can help design professionals to better understand not only many aspects of curtain wall systems but also how such systems may affect other building systems they work with. The book can also help with more efficient design of building structural and envelope systems. The book is deemed appropriate as a textbook for students in civil and architectural engineering and architecture programs and also as a reference for building owners, architects, engineers, fabricators, contractors, and building code officials.

CHAPTER 1

INTRODUCTION

Faron A. Morris

The architectural appeal of glass comes from its most obvious properties—light reflectance and transmittance. In daylight, glass reflects its surroundings. On a high-rise tower blue sky is seen reflected on a clear sunny day, clouds on an overcast day, and lit offices at night. Glass gets your attention. The dynamic, always-changing appearance of a glass-clad tower is not possible with any other building material. Light transmission allows natural indoor lighting and a view from inside the building, providing a closer connection to the natural outdoor environment. Reflectance and transmittance—properties unique to glass—have increased its popularity and use in multistory construction.

The wall of glass seen in high-rise construction is a sophisticated manufactured product called curtain wall. Separating and moderating the interior building environment is its primary function. As an environmental separator it must keep out air and water; reduce heat loss in cold weather and reduce solar heat gain in warm weather; safely support wind loads, which become significant on high-rise buildings; accommodate thermal movement due to temperature fluctuations throughout the day and changing seasons; and accommodate building interstory movements caused by wind, live, and seismic loads. In certain geographical locations, extreme events require special design consideration for impact forces from flying debris in hurricane winds or large interstory movements caused by seismic events. Other special design considerations include reducing fire spread from floor to floor or across a floor at the structural slab edge and preventing injury to occupants from a blast event.

This primer will highlight the materials used in the manufacture of curtain wall in high-rise construction and discuss specialized aspects of curtain wall design and analysis for extreme events such as earthquakes and bomb blasts. This information is not readily available because the curtain wall industry is relatively young compared with other well standardized construction industries such as structural steel, timber, and concrete. Material-specific information is spread across the glazing, sealant, plastic, and aluminum extrusion industries and is not generally taught in college or university courses, though in recent years architectural engineering programs are focusing more on building science and cladding. This primer compiles a basic review of the many aspects of curtain wall and current topics that affect the design and performance of curtain wall all in one document.

This primer's focus is on factory-assembled (unitized) and site-assembled (stick system or stick built) curtain wall in which transparent glazing is the predominant infill. Types of cladding not addressed in this primer include punched windows, strip windows, skylights, structural glass, and point-supported glass façades.

This primer is written for the individual outside the curtain wall manufacturing and consulting industry who possesses little to modest prior knowledge and wants to learn more about this specialized field. The target audience for this primer comprises architects, structural engineers, HVAC engineers, general contractors, building owners, and building operators.

CHAPTER 2

DEFINITION AND TYPES OF CURTAIN WALLS

Faron A. Morris

Also known as cladding or building façade, curtain wall is the skin of a building; its primary function is as separator or boundary between interior and outdoor environments. Curtain wall is light compared with other façades such as masonry and precast, and its name derives from the way it hangs from the structure like a curtain. Thus curtain wall is non-load bearing, meaning it supports no vertical structural loads aside from its own weight.

Several definitions regarding the production of curtain wall are worth mentioning to aid in understanding the processes involved. These are fabrication, assembly, glazing, and installation. Fabrication encompasses all machining operations, including cutting, drilling, milling, and punching. These operations are performed on the aluminum extrusion framing members. Assembly involves the fastening together of aluminum framing members to create a frame to support the glazing infill. Joints in the frame need to be covered with sealant to make the frame air and water tight. Insulation is attached to spandrel openings. Glazing involves attaching the infill to the vision or spandrel frame opening. The most common infill is an insulated glass unit but also can be an aluminum, stainless steel, or granite panel. A vision or spandrel frame opening is the area between aluminum framing members occupied by an infill. Installation pertains to any work performed on the construction site.

The two types of curtain wall are characterized by the manner in which they are produced: stick built and unitized. Stick-built curtain wall is fabricated in the shop and shipped in pieces to the site where it is assembled and glazed. The installation process combines assembly and glazing, because most of the wall production occurs onsite. Stick-built walls have higher site labor costs (site labor is generally costlier than shop labor), because most of the assembly and glazing takes place there, which also results in a longer schedule to enclose a building. However, the biggest drawback of stick-built systems is that installation (assembly and glazing) is done outdoors in full exposure to the weather. Sealants are an important component of curtain wall that prevent air and water infiltration. Sealant durability depends on good adhesion to the joint surfaces they are sealing, and good adhesion requires clean and dry joint surfaces, which can be difficult to obtain in variable weather conditions outdoors. Regulated temperature and humidity, such as exists in an indoor environment, are conducive to more reliable sealant application.

Stick-built walls are assembled on the building and consist of tubular aluminum profiles. Mullions are assembled first, then horizontals are fastened to the mullions with clips or spigots. Glazing begins once enough framing has been installed and progresses up the tower to complete building enclosure.

Unitized curtain wall is fabricated and assembled at the manufacturer's shop, then shipped to the site for installation. Unitizing benefits from indoor assembly and glazing, because a controlled environment improves curtain wall durability. The time required to close in a building is greatly reduced with unitized systems because most of the production is done in the shop. Installation simply involves placing preassembled and preglazed frames on the building. Often unitized curtain wall installation follows immediately after erection of the structure. As a result, building close-in time is greatly reduced. Unitizing requires split members that interlock with the adjoining frame in a male-female interlocking method that incorporates gaskets for a joint that is both air and water tight.

A building clad with reflective glass may appear to be all glass, but curtain wall consists of more than just glass. Typical curtain wall is made up of transparent vision glass and opaque spandrel-glass infills supported by a metal framework of aluminum extrusions (Fig. 2-1). Other commonly used infills are stainless steel panels, painted or anodized aluminum panels, granite, marble, limestone, combination glass and metal panel (called a shadow box), louvers, and vents. Spandrel infills are insulated for increased thermal performance and opaque (nontransparent) to hide the slab edge and ceiling cavity. A typical spandrel infill consists of insulation adhered to a galvanized steel sheet called a backpan or foil back insulation, premanufactured insulation adhered to aluminum foil, inboard of a single lite or insulating glass unit (IGU). The backpan or foil is the air-vapor barrier preventing air and water from infiltrating to the interior. Because of its brittle nature, glass requires contact with soft materials called glazing gaskets such as high durometer (rigid) rubber or silicone to prevent breakage. Low durometer (soft) rubber or silicone gaskets are used at split vertical and horizontal members to form seals against air and water. Preventing air and water infiltration to the interior is a major

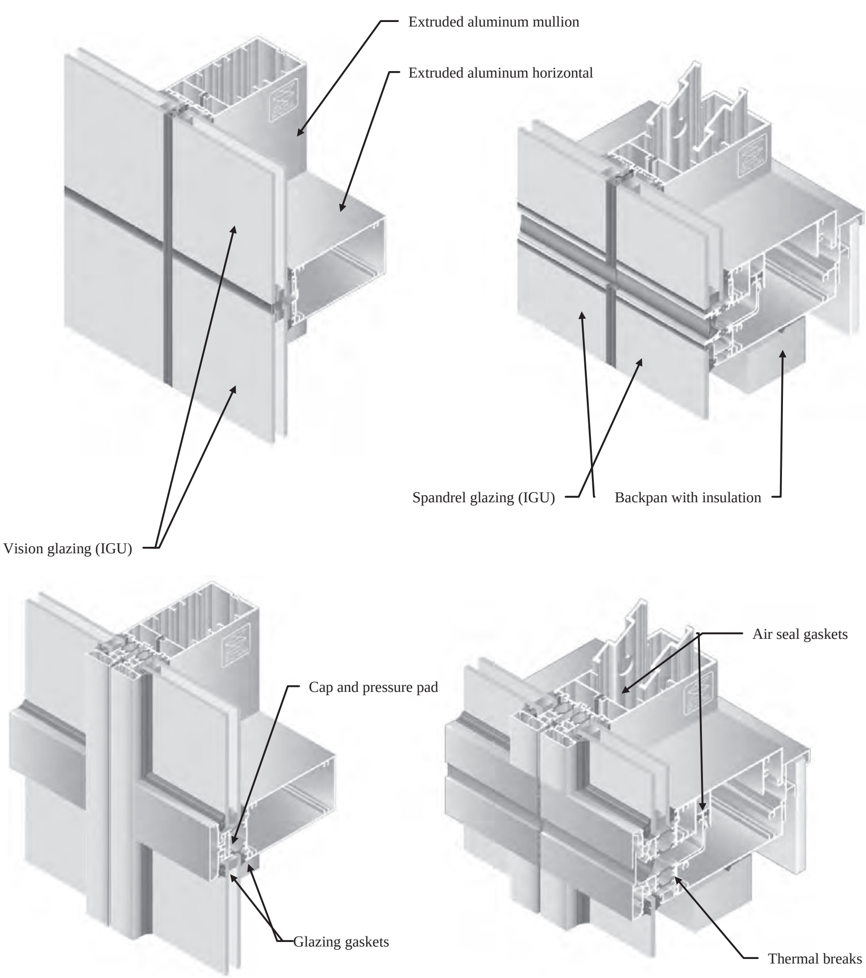


Fig. 2-1. Unitized curtain wall components
Source: Thermo3 Series Curtain Wall System, courtesy of Sota Glazing, Inc., Brampton, Ontario, Canada

function of curtain wall. Glass and extruded aluminum are intrinsically nonporous to air and water, but at frame joinery where aluminum members connect, hair-line gaps between extruded aluminum framing members require sealing with sealant or tape. Because aluminum is highly conductive, thermal performance is obtained by separating inboard aluminum extrusions from outboard extrusions with thermal breaks. These are made from plastics, such as PVC or nylon (polyamide), to improve thermal performance by physically separating highly conductive aluminum extrusions. The low-conductivity plastic separates exterior extrusions from interior ones to reduce heat loss through conduction and prevent condensation in heating-dominated climates and heat gain in cooling-dominated climates.

The aluminum extruded members that comprise a curtain wall frame have specific names shown in Fig. 2-2. The vertical extrusions are called mullions or verticals. They support the infill and horizontals by carrying lateral wind loads and infill self-weight to the anchor. The top horizontal member in the vision opening is called the head or header. The bottom horizontal member in the vision opening is called the sill. An intermediate horizontal with vision or spandrel above and below is called an intermediate horizontal. The mating horizontals at the split between two frames are called the expansion joint members. Horizontal members are also referred to as transoms or rails. Horizontals carry wind load to the mullion and the self-weight of their infill materials.

Frame openings are areas glazed with one of the previously described infill materials. Vision openings contain a transparent IGU that can be double or triple glazed with one or more lites that are tinted (colored), mirror coated, or low-e coated. Spandrel openings contain nontransparent (opaque) infill materials, including glazing with opaque coating and are insulated for increased thermal performance.

The way glazing is retained by the framing has a visual effect on curtain wall's appearance and provides a degree of creative freedom for the architect specifying the wall. Two methods called capped systems and structural silicone glazed systems use distinctly different means of glazing retention. Capped systems physically hold the glazing infill with aluminum extrusions, combined with rubber glazing gaskets, to lock it to the frame. From the outside the glazing appears to have a picture frame of painted or anodized aluminum around it. There are variations of capped systems where all four sides can be captured, called four-sided captured systems. Any combination is possible, including horizontally captured and vertically siliconed and vice versa. Random or patterned cap locations across an elevation are also options. The profile of the cap can be any shape possible within the limits of the aluminum extruding process.

Structural silicone glazed (SSG) systems employ structural silicone sealants that adhere the glazing to the frame—effectively gluing the glazing to the frame. Structural silicone sealants have been engineered using advanced chemistry to create a safe and reliable product for this specific application. The visual difference is a cleaner, uncluttered appearance, giving the impression, from a distance, of a wall of continuous glass. The thin joints between frames seem to disappear at a distance.

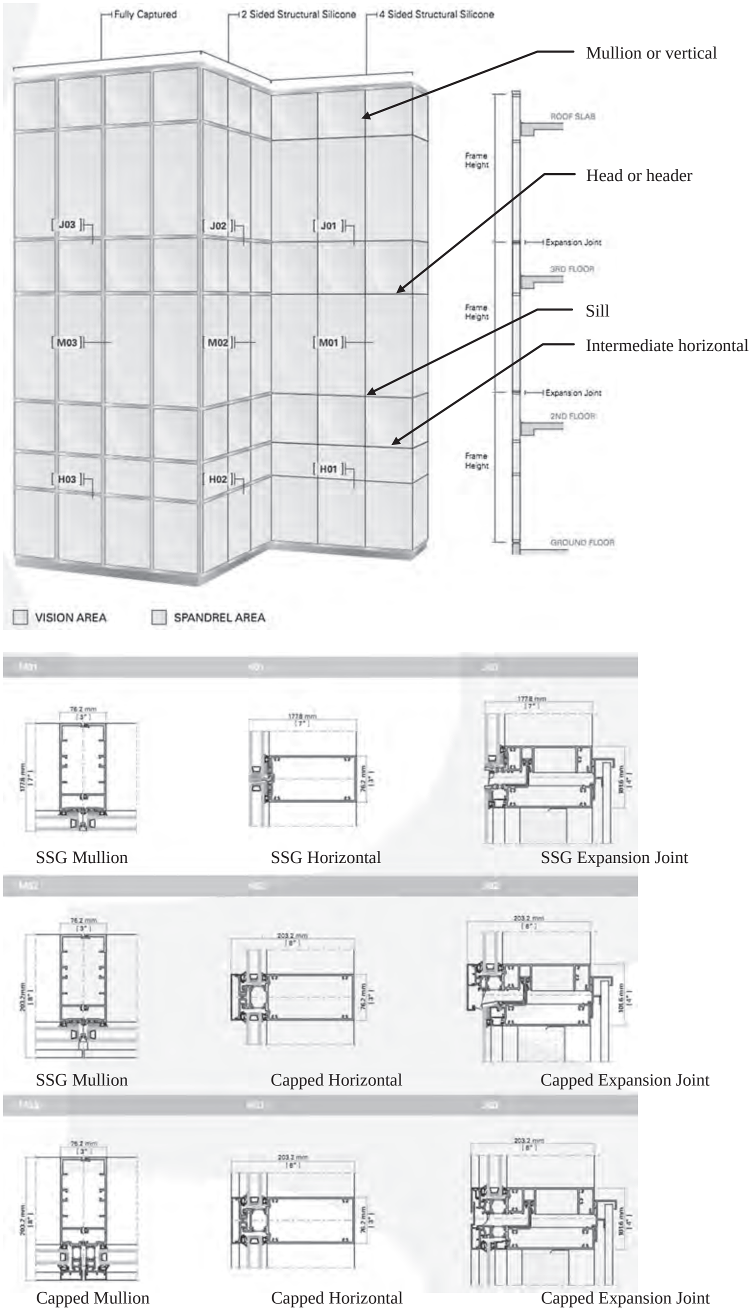


Fig. 2-2. Typical curtain wall elevation featuring SSG and capped glazing Source: Thermo3 Series Curtain Wall System, courtesy of Sota Glazing, Inc., Brampton, Ontario, Canada

CHAPTER 3

MATERIALS AND CONFIGURATIONS

Dudley G. McFarquhar, Ph.D., P.E.

This chapter provides an overview of some common materials used with curtain wall systems and some different configurations of some elements. Note that curtain wall systems are proprietary and consist of multiple components. For that reason, this chapter presents an overview of these systems' basic parameters.

Curtain wall is a term that describes a building envelope component. It is a nonload bearing façade that provides protection from the exterior environmental elements. A curtain wall system typically comprises extruded aluminum framing with infill glazing or opaque substrates. The curtain wall does not provide any stiffness to the building structure. Whereas curtain wall framing supports its internal elements, the frame itself is supported by the building structure.

The curtain wall is subjected to critical environmental elements including lateral loads (e.g., wind, seismic), temperature, humidity, moisture, and defined building movements. In special cases, the curtain wall can also be designed to mitigate forces from hurricanes, missile impact, and blast loads.

3.1 MATERIALS

Curtain wall comprises clear and opaque elements that are critical to its performance and longevity. The clear component is predominantly glazing (Fig. 3-1), while the opaque areas may consist of myriad components: opaque spandrel glazing, metal panels and louvers, natural stone (Figs. 3-2 and 3-3), concrete panels, and glass fiber–reinforced concrete (GFRC) panels.

Fig. 3-1. Winspear Opera House, Dallas, TX; an example of all clear glazed façade
Source: McFarquhar Group Inc.; reproduced with permission

Fig. 3-2. One Shell Square, New Orleans, LA; an example of a high-rise building with a glazing and natural stone façade
Source: McFarquhar Group Inc.; reproduced with permission

Fig. 3-3. Kuala Lumpur City Centre, Kuala Lumpur, Malaysia; an example of glazing and metal panels
Source: Courtesy of Thornton Tomasetti; reproduced with permission

3.1.1 Glazing

Glass is a very important architectural component of a curtain wall system. It provides the building occupant vision to the exterior and introduces daylight to the interior space. The concepts of energy impact on a building as well as energy transfer is very important to the glazing makeup and its performance. Energy has always been a critical component of the research done by the differing glass unit manufacturers and is an ongoing issue that is being reviewed closely by the glazing and related industry communities. Glass is characterized by type, color, size, and strength.

Glass Type The type of glass units can be assigned to three basic groups: monolithic, insulating units, or laminated lites (GANA 1997). Monolithic glass comprises a singular thickness. It is usually used in various thicknesses ranging from 6 mm (1/4-in. nominal) in spandrel glass to 12 mm (½-in. nominal) for glass handrails, or thicker as needed for strength aesthetics and other parameters, for example, in some lobby glass applications depending on the supporting curtain wall framing application. It is also used in glass-mullion applications and can be an element such as a glass fin.

Insulating glass unit describes a glazing assembly of two glass lites separated by an air space. For example, a 25 mm (1-in. nominal overall) insulating glass (IG) consists of two 6 mm (¼-in. nominal) thick glass lites with a 12 mm (½-in. nominal) thick air space. Insulated glass has four glass surfaces numbered 1 through 4 from exterior to interior (Fig. 3-4). These surfaces allow the glazing unit to incorporate elements such as tints and low emissivity (low-e) coatings, thus modifying the amount of light and energy transmitted into the interior space. Depending on the level and color of tint, the reflectivity is also affected. For example, a silver-tinted glass is highly reflective, whereas darker tints absorb the light. Other elements such as photovoltaic cells can be used to generate energy in insulated glazed units. This higher technology with cell placement and wiring, however, adds some cost to the glazing system. Insulated glass can also be used in structural glazing applications, which will be discussed later in the chapter.

Laminated glass describes an assembly consisting of multiple layers of monolithic glass lites assembled with a laminate interlayer membrane between the lites. The interlayer thickness varies from 0.04 mm to 0.23 mm (0.015 to 0.090 in.). Combinations of two or three glass lite laminates are

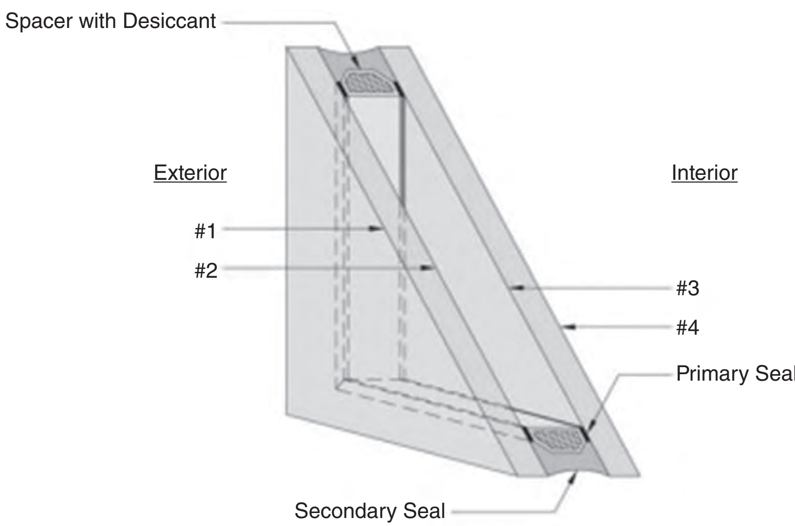


Fig. 3-4. Insulated glass unit makeup
Source: GANA Glazing Manual: 50th Anniversary Ed. (GANA 1997); *reproduced with permission from Glass Association of North America (GANA), www.glasswebsite.com*

common for different applications. Considering that these combinations increase laminated glass lites strength, they are used in a variety of applications. They can be incorporated in insulated glass units for missile impact resistance or sound transmittance. Other applications include forced entry protection and safety applications in overhead glazing such as skylights (Fig. 3-5).

Glass Color Glass color has become an important feature in characterizing building façades (Fig. 3-6). Manufactured glass has an inherent natural greenish tint due to the iron content in the glass. Clearer glass

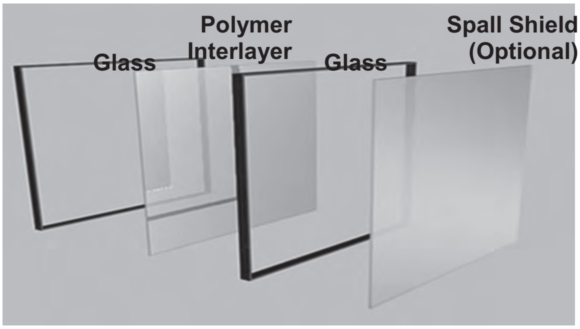


Fig. 3-5. Representation of laminated glass makeup
Source: McFarquhar Group Inc.; reproduced with permission

Fig. 3-6. Winspear Opera House, Dallas, TX; example of unique glass color to define aesthetics
Source: McFarquhar Group Inc.; reproduced with permission

can be made by reducing the iron content, and now such low-iron glass is available commercially. Another method of introducing color into glazed façades is to use tints on the #2 or #3 surface of an insulated glass lite unit. Myriad colored tints can be used in combination, such as a reflective tint combined with a low-e tint to reduce the heat transfer through a glass unit. The spandrel glass lite is opaque and can be monolithic or insulated units with the back interior #3 surface painted.

Glass Size Glass size limitations are primarily related to the limitations of the float plant or autoclave that provides tempering of the glass lite and the loading requirements. The size of glass lites is also limited based on the individual lite thickness. For nominal usage in commercial glazing, 6 mm (¼-in. nominal) thick glass is used for insulated glass and laminated glass lites, but size can vary depending on the application and loading constraints.

Glass Strength Glass strength is described by three categories: annealed, heat strengthened, and fully tempered. Note that glass is strong in compression but much weaker and susceptible in tension.

Annealed glass (AN) is float glass, based on its unique manufacturing process. It is fabricated in a continuous flow and cut into large sheets, which are then cut into smaller lites as needed. On a relative scale of strength factor (SF), annealed is the weakest with an SF of 1.

Heat-strengthened glass (HS) is float glass that has been passed through a quick cooling process. This cooling process develops a compression layer on the exterior surfaces, which inherently increases the strength of the glass. A relative SF of about 2 is common for this kind of glass, suggesting that HS glass may be as much as twice as strong as AN glass.

Fully-tempered glass (FT) is float glass that is subjected to a controlled quick temperature cooling process, which significantly increases the strength within the compression layer in the glass lite. An SF of 3.8 to 4 is common, suggesting that FT is nearly four times as strong as annealed glass. An application of this glass type is used for safety glazing because of the small cubes or shards that result from glass breakage in failure mode. The size of the shards minimizes the potential for damage. Nominal tempered glass units are designated in buildings with a label as "knock out" lites in case of an emergency for access or exit.

3.1.2 Natural Stone

Natural stone is incorporated in many curtain wall projects as accent perimeter bands, column covers, or spandrel covers. Natural stone types are varied and include granite, limestone, sandstone, travertine, and marble. Travertine and marble tend to be more suited for interior work because of their response to exterior weathering effects. However, their intricate veining provides a lot of aesthetic options for architects. More traditional stones, such as granite and limestone, may be incorporated into a curtain wall system as individually installed supported panels referred to as "handset stone" (Fig. 3-7) or individually supported on steel frame trusses referred to as stone trusses (Figs. 3-8 and 3-9).

Fig. 3-7. Naples Philharmonic Museum, Naples, FL; an example of natural stone façade (granite)
Source: Courtesy of Thornton Tomasetti; reproduced with permission

Fig. 3-8. Stone truss panel being installed
Source: Courtesy of Atlantic Exterior Wall Systems, LLC; reproduced with permission

Fig. 3-9. Stone truss panel being hoisted from transportation vehicle; note the steel frame back-up behind the stone panels
Source: Courtesy of Atlantic Exterior Wall Systems, LLC; reproduced with permission

Several methods are used for stone attachment, such as stainless steel anchors, aluminum extruded anchors, dowels and epoxy, and mechanical anchors (such as Type 31 anchors). Type 31 anchors include a custom "keyed" slot in the stone that allows the anchorage to be concealed. Stone panel thicknesses vary from 3 cm (1¼ in.) to 5 cm (2 in.) in granite and travertine, whereas limestone can vary from a minimum thickness of 5 cm to large cubic projecting profiles such as cornices and columns on courthouse projects. Available references, such as the Marble Institute of America (MIA, 2011), the Indiana Limestone Institute Design Manual (ILI, 2007), and others provide guidelines for stone attachment and profile concept. However, an important recommendation for all stone cladding is the need for stone panel component connections to be designed and reviewed by a registered professional engineer or architect. Natural stone is a material (Fig. 3-7) that needs testing to determine appropriate safety factors. Due to the variety of stone types available on the commercial market, a careful visual review is required to estimate their project performance.

3.1.3 Precast Concrete Panels

Precast concrete panels are typically used for column covers and horizontal spandrel covers. They are often fabricated in long lengths depending on the modular grid of the project and often provide the perimeter

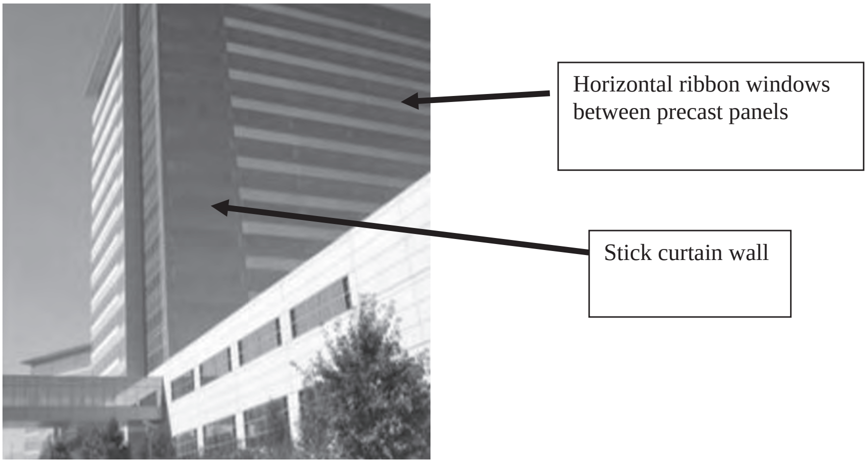


Fig. 3-10. Blue Cross Blue Shield, Richardson, TX; an example of multiple façade types on a building
Source: Courtesy of Corgan Associates; reproduced with permission

support for infill windows such as ribbon windows (Fig. 3-10). The exterior of the panels can be articulated during the forming process to express a certain architectural intent. They are connected to the building structure with very heavy, specially designed connections, such as embeds, because of the size and the weight of the panels.

3.1.4 Glass Fiber–Reinforced Concrete (GFRC) Panels

Glass fiber–reinforced concrete panels are lighter than precast concrete panels and consist of a thin concrete mixed with reinforcing fiber. These panels can be formed to different sizes and profiles. However, they require a sufficient amount of anchors for internal load distribution and localized response to lateral loads.

3.1.5 Metal Panels

The two types of metal panels are monolithic and composite. Monolithic panels can be glazed into curtain wall framing similar to glass, and composite panels can be individually installed on backup track systems. Composite panels are a laminate of two thin exterior metal plates with an inner layer of insulation. They provide additional thermal characteristics such as heat gain reduction and heat loss from the interior space. The panel installation can be accomplished by a dry-glaze method or a wet-glaze method with sealant, depending on project conditions. Anchorage of these panels is generally accomplished with fasteners to return edges of the panels.

With respect to panel structural performance, metal panels include certain intrinsic design features, such as ribbed or embossed panel profiles, that actually provide additional stiffness to the plate and prevent an aesthetic perception of bowing or "oil canning." Along with the architectural profile, the choices of high-end finishes and colors provide a plethora of possibilities, thus allowing great aesthetic flexibility in the coverage of building façade square footage (interior or exterior).

3.2 CURTAIN WALL FRAMING ELEMENTS

Commercially available curtain wall framing elements are primarily extruded aluminum and/or steel framing (AA 2000). The choice depends on the aesthetic choices made for the façade, module spacing, and grid and load considerations.

3.2.1 Aluminum Curtain Wall

Conventional curtain wall framing systems comprise aluminum framing with glazed openings (glass, metal panels, or natural stone).

Aluminum framing is available in different system depths for the vertical and horizontal elements. The profiles can be open or closed depending on the application. One of the significant architectural advantages of using aluminum framing is that multiple profiles can be readily extruded to develop special shaped framing or accent profiles such as bullnoses. The extrusions generally have sharp edges (except for curved profiles), which accentuates a clean finish. Multiple layers of coating protect the aluminum metal depending on the project specifications, whereas the system depth is primarily dictated by wind load requirements. Figs. 3-11 and 3-12 show examples of aluminum frame systems. These frame elements are assembled by fasteners and shear elements and can be field assembled or factory assembled depending on the system and scheme of installation.

Note that some verticals appear to have a closed shape, but they often have open three-sided profile shapes with a closure snap that creates the appearance of a closed shape. This concept is used in some cases for installation sequence and access to anchorage of the top and bottom horizontal members. Several manufacturers in the industry produce custom shapes and systems. This chapter will not discuss particular nuances of individual systems because such information is proprietary.

In general, the design performances of these elements are governed by local and national building codes, such as the International Building Code (ICC, 2006), ASCE 7-10 (ASCE 2010) Wind Load Codes, and guidelines by

Fig. 3-11. Tubular mullion system
Source: Courtesy of Oldcastle BuildingEnvelope®; reproduced with permission

Fig. 3-12. Tubular mullion system
Source: Courtesy of Oldcastle BuildingEnvelope®; reproduced with permission

Fig. 3-13. Examples of available literature or code guidelines
Source: McFarquhar Group Inc.; reproduced with permission

the American Architectural Manufactures Association (AAMA 1987, 1989; Fig. 3-13). These publications establish limits for deflection and stresses. Because the aluminum frames are extrusions, they can consist of different alloys. The more common aluminum framing alloys are 6061-T6, 6063-T5, 6063-T6, and 6005-T5. Depending on the alloy temper, they have differing stress characteristics. For metal comparison, aluminum alloys 6061-T6 and 6005-T5 are nearly as strong as steel in yield strength. Figure 10 provides an example of some of the guideline literature used over the years and available for designing these systems. These manuals are constantly being updated and adopted by the varying local jurisdictions at different time intervals.

3.2.2 Aluminum Framing Systems

There are two main categories of curtain wall systems assemblage: field-assembled systems, commonly referred to as stick systems (Fig. 3-14), and shop-assembled systems, referred to as unitized systems (Figs. 3-15 and 3-16). Unitized system refers to module-size units that are preassembled. These frame types are generally split mullions (i.e., they have two mating profiles) with horizontal subframing. The glass is generally structurally bonded to the framing using structural grade silicone,

Fig. 3-14. Great America Building, Cedar Rapids, IA; example of stick wall system
Source: Courtesy of Wausau Window and Wall Systems; reproduced with permission

Fig. 3-15. Unitized or shop-assembled system
Source: Courtesy of Oldcastle BuildingEnvelope®; reproduced with permission

Fig. 3-16. Unitized or shop-assembled system
Source: Courtesy of Oldcastle BuildingEnvelope®; reproduced with permission

which requires close monitoring and quality control during the sealant application and cure time. In this case, the glass is "adhered" to the aluminum framing.

The system type suitability is often a function of the job site constraints. Both systems can be installed properly. These are some of the advantages of unitized wall systems:

- The assemblage is done in a controlled shop environment.
- Erection is completed more quickly.
- Horizontal wrapping of floors provides more a systematic building envelope closure.
- There is less handling of components in the field.

The most critical function that the curtain wall is expected to perform is air and water infiltration control. Air is controlled by baffles at weep hole locations, rubber gaskets (i.e., wedge or wiper), air membrane and perimeter sealant at the framing or sill pan conditions depending on the system. Water infiltration is controlled by perimeter sealant and an internal weepage system that facilitates the exterior discharge of any water that collects inside the glazing pocket of the framing. Weep holes with supporting baffles that prevent dirt and bugs from accumulating inside the framing cavity are located in horizontal elements.

3.2.3 Steel Framing and Elements

Steel backup framing is used in several curtain wall systems. The steel framing can be implemented as individual elements, such as frame "sticks," or as an assembly in trusses. Both horizontal and vertical trusses are used. Horizontal trusses may be used for stone panel support by developing module units. For natural stone, such as granite, steel trusses consisting of a combination of steel channels and/or tubes are used to support individual stone panels.

Vertical trusses such as bow trusses or tube pipe trusses, can be used to support glazing. These truss types provide the backup stiffened element that provides the main resistance to lateral loading and transfer these loads back to the building structure. Often these trusses can be assembled in combinations, for example on a large skylight to span across larger openings, as depicted in Fig. 3-17.

Another steel element that has design elegance due to transparency is steel cables used in cable net walls (see the example in Fig. 3-18). These cables are pretensioned and provide a more transparent look to the façade with minimal framing. However, the perimeter anchorage for this system must be robust and properly designed because cables are only strong in tension. For these systems, the deflection allowed is significantly greater than it is for traditional framed systems. However, significant cost is associated with these wall types in comparison with traditional metal-framing systems.

Fig. 3-17. Winter Garden, New York (at World Trade Center)
Source: Courtesy of Thornton Tomasetti; reproduced with permission

Fig. 3-18. UBS Tower, Chicago, IL; example of a cable net wall
Source: Courtesy of Thornton Tomasetti; reproduced with permission

The steel truss and cable net wall offer some unique attachment configurations for vertical glass, sloped glass, or transitioning façades such as corners. They are all custom fittings fabricated for the particular application.

3.3 TYPES OF GLAZING PANEL CONSTRUCTION

The following section discusses several methods of constructing or installing glazing panels, including dry glazed, wet glazed, structural silicone glazed (SSG), point supported, cable net, and double skin walls.

3.3.1 Dry Glazed

Dry-glazed application refers to the use of rubber gaskets, and structural tape in some cases, thus using compression to restrain the glass unit or metal panel inside the glazing pocket of the framing (Fig. 3-19). The rubber gaskets are extruded and custom profiled with darts for retention inside the manufacturer's custom system. Typically, the rubber gaskets are on either side of the glazed element, and the wedge gasket is the primary compression-applied element. Depending on the system, panels can be glazed from the interior or exterior.

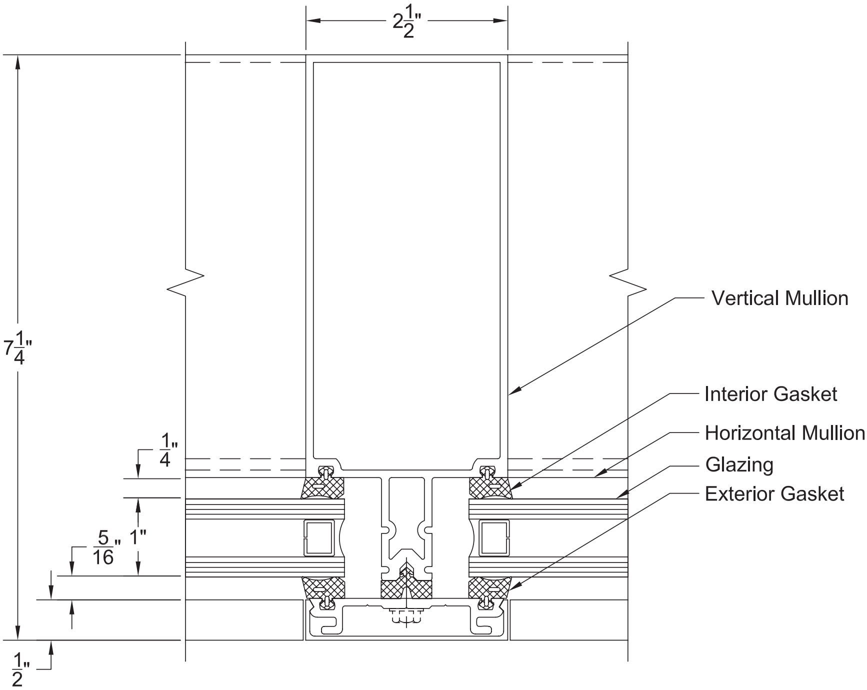


Fig. 3-19. Example of dry-glazed system with rubber gaskets (plan view)
Source: Courtesy of Oldcastle BuildingEnvelope®; reproduced with permission

3.3.2 Wet Glazed

Wet glazed application refers to the incorporation of silicone sealant as a primary element for attaching or installing the infill element. The process involves applying an external perimeter seal. Proper perimeter preparation is required for the sealant to function adequately.

One specific type of wet-glazed application is structural silicone glazed (SSG). SSG application requires careful preparation and monitoring of the sealant. The process involves adhering the glazed element to an aluminum frame. The bond between the silicone, the glass, and the aluminum frame provides structural resistance to lateral loading (Fig. 3-20). The recommendation is to conduct this installation process in a shop or factory clean environment because the sealant adheres less well to the dusty surfaces that would be typical in the field. The required contact width is a critical component for the structural integrity of the system based on safety factors such as sealant stiffness and stress capacity. SSG units may be fabricated for single- or two-floor heights (Fig. 3-21).

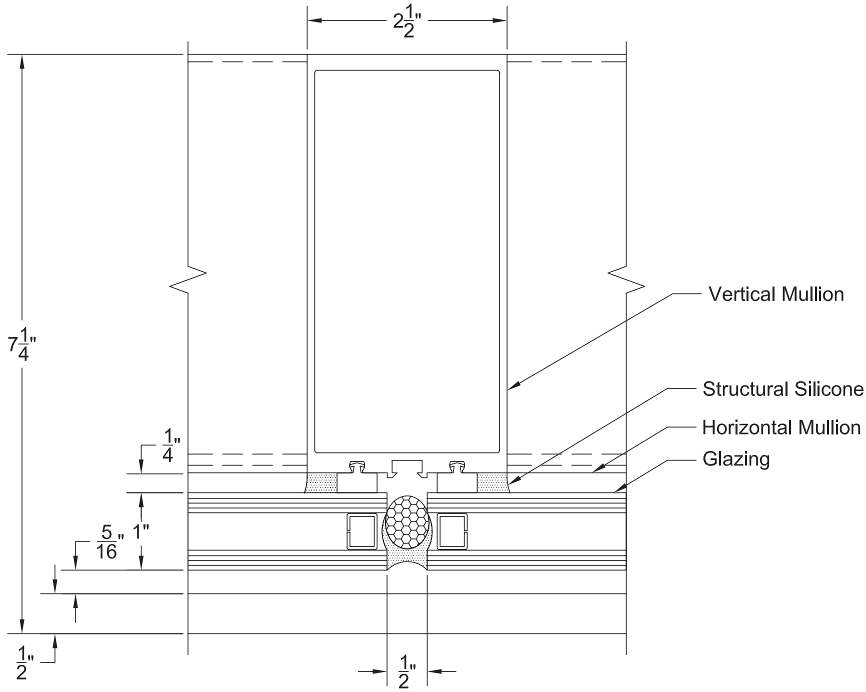


Fig. 3-20. An example of SSG application (plan view)
Source: Courtesy of Oldcastle BuildingEnvelope®; reproduced with permission

Fig. 3-21. Installing a structurally glazed unit in Ft Worth, TX
Source: Courtesy of Harmon Inc.; reproduced with permission

3.3.3 Point-Supported Glass Systems

Point-supported systems are custom and job specific in application and fittings (Figs. 3-22 to 3-24). The fittings are often driven by the architectural intent, and molds can be fabricated with a high level of engrained aesthetics and precision. The detailing is often elegant but requires a lot of coordination and dye control. This type of system requires proof testing of prototypes especially if the project has high complexity or geometrical challenge. The analysis of these systems often involves sophisticated finite element modeling to evaluate load transfer and stresses within and by the fitting elements.

3.3.4 Cable Net

As previously mentioned, the cable net wall is an elegant but somewhat expensive façade. The framing siteline is minimal and offers tremendous visual clarity for the patron (Fig. 3-25). However, it requires rigorous structural analysis and field coordination because of the resulting effect of loading on the structure. Because of the flexibility of the wall, the deflection under high lateral loading conditions may seem excessive and uncomfortable, but the wall functions well and serve its aesthetic requirements.

Fig. 3-22. Newark International Airport, NJ; example of point-supported glass and glass fins
Source: Courtesy of W&W Glass, LLC; reproduced with permission

Fig. 3-23. Complex glazing connections; example of point-supported glazing
Source: Courtesy of W&W Glass, LLC; reproduced with permission

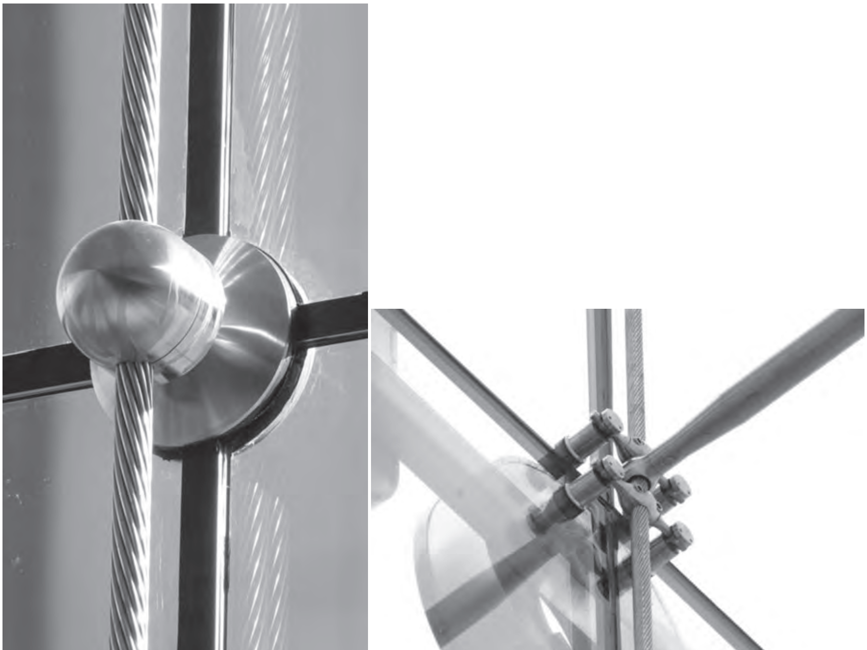


Fig. 3-24. Examples of point-supported glass fittings
Source: Courtesy of W&W Glass, LLC; reproduced with permission

Fig. 3-25. UBS Tower, Chicago, IL
Source: Courtesy of Thornton Tomasetti; reproduced with permission

3.3.5 Double Skin Wall

This type of curtain wall system is quite complex and duplicates the number of clad walls. It uses the cavity between the façades to control energy input from daylight and to incorporate mechanical ventilation using the warm air within the cavity space. It is commonly used in Europe and other regions. It is a more expensive wall compared with other, more conventional curtain wall systems. This wall type generally includes louvers, operable windows, sunshades, etc., with the focus and emphasis being placed on energy recycling as an everyday operation of the building. An example of a double skin façade is shown in Figs. 3-26 and 3-27.

3.4 CURTAIN WALL ANCHORAGE

The curtain wall is uniquely anchored to the building at floor lines. The mode of attachment depends on the spans, wind or seismic loading, and temperature. The curtain wall can be supported by

Fig. 3-26. University of Southern California Stem Cell Research Facility, Los Angeles, CA
Source: Courtesy of W&W Glass, LLC; reproduced with permission

Fig. 3-27. University of Southern California Stem Cell Research Facility, Los Angeles, CA
Source: Courtesy of W&W Glass, LLC; reproduced with permission

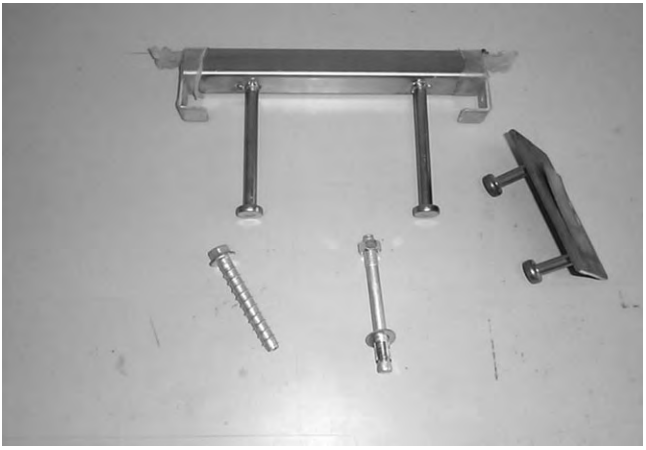


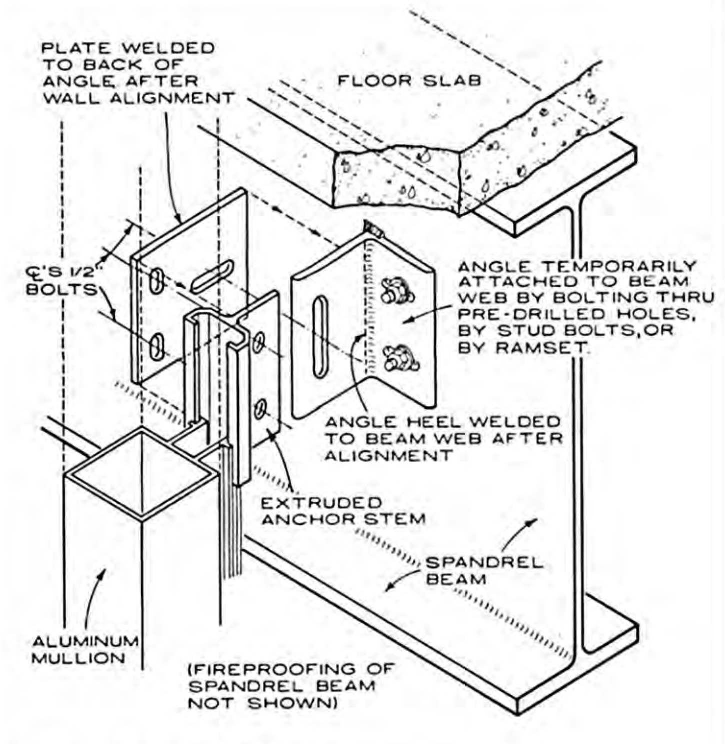
Fig. 3-28. Examples of curtain wall framing anchorage
Source: McFarquhar Group Inc.; reproduced with permission

- Extruded aluminum anchors;
- Steel plate anchors or steel angles (in either case with separator pads between dissimilar metals, i.e., aluminum and steel); and
- Steel bolts (through bolts or tapping bolts).

The anchorage attached to the building may be steel embed plate, steel channel anchors, welds, expansion bolts, and epoxy anchors (Figs. 3-28 and 3-29). Each method has its merits and must accommodate anticipated building movements and construction tolerance. These connection elements are generally in the spandrel areas and hidden from normal view. Curtain wall framing connections must be engineered for imposed loading constraints. Because perimeter conditions and wind loading vary from project to project, anchorage schemes should be evaluated on a project-specific basis. In fact, the wind loads on various parts of the building can be quite different, so attachment design may vary even on the same building project.

3.5 SUMMARY

The performance of the curtain wall façade remains the most important critical component of a building's defense against the exterior environment. At the microscopic level, the curtain wall requires a high level of detail for intricate components, extrusions, and their attachments; at the macroscopic level, the curtain wall defines a building with multiple material and configurations available.



Movable anchor attached to face of spandrel beam

Fig. 3-29. Representation of curtain wall frame anchorage
Source: AAMA Curtain Wall Manual *(AAMA 1987, 1989). Courtesy of American Architectural Manufacturers Association; reproduced with permission*

As initially stated, curtain wall systems are very custom and proprietary. Several manufacturers develop unique systems to withstand wind loading, hurricane winds, blast loading, seismic loading, missile impact, and thermal and live load movements. All of these systems can have excellent features. Projects can be customized or use off-the-shelf systems. Having multiple curtain wall systems within the exterior façade of a particular building or complex is common. This combination of systems can use a variety of elements such as glazing, natural stone, concrete, and metal panels. The curtain wall systems also allow appendages, such as sunshades and aesthetic bullnose accent profiles, to be designed and supported within their gridwork.

The curtain wall represents the signature of the building. It is integral in expressing the intended geometric shape of the building and defining the façade's modular grid. Using available tint options allows the architect a wide range of hues to work with and manufacturer test data can enable energy studies to be conducted on the basis of either selected color or glass type scheme.

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CHAPTER 4

TESTING MOCKUPS AND FIELD INSPECTION

Dudley G. McFarquhar, Ph.D., PE

Testing has proven invaluable to the performance (actual and expected) of curtain wall systems. Different types of testing can be implemented. Testing is often job specific and a function of the building-envelope complexity, project size, number of system types, and building usage.

Sequencing of testing is primarily done in two phases:

1. Prior to building construction by the testing of a mockup
2. In-field testing at different stages during construction

Testing of the curtain wall system provides valuable information about potential problems or validation of expected performance. It can be a great learning tool, especially in the scenario where multiple systems types and materials interface within the building envelope. Because all subcontractors are responsible for their scope or material type, the challenge always occurs at interfaces and in the necessary coordination among different trades.

Along with testing, field inspection of curtain wall installation is critical. Typical questions related to field inspection include the level of review required for a project, who will provide this review, how often will the review occur, and who has responsibility on the back end.

4.1 MOCKUPS

Mockups are prototypes representing and replicating sections or portions of the curtain wall system or building envelope. They often encompass aluminum framing, glazing, natural stone panels, metal panels, or other perimeter materials as dictated by the project. The mockups can be constructed of different sizes and, if being tested in a laboratory, be limited to the laboratory test chamber's dimension or capability.

Mockups comprise basically two types: visual and performance.

4.1.1 Visual Mockups

Visual mockups are constructed primarily to review relative location of elements, finish of material, joinery (framing, wall, metal panels, and sealant), aesthetics of the curtain wall, and interior view of material finish and layout (Fig. 4-1). The visual mockup often is used as a benchmark for expected quality of material and consistency in installation and enables the contractor/subcontractor to demonstrate to the owners and the design team that the work will be properly executed to industry standards. Punched windows represent a good example in which the interface with the perimeter waterproofing needs to be coordinated and demonstrated. In several instances, the manufacturer's representative is involved to provide additional guidance to the subcontractor if needed. This element is important for maintenance of material warranty on the project. The visual mockup represents a cost-effective means of making changes in materials or colors prior to mass construction of the building. Architects especially like to use aesthetic mockups to explore or review different

Fig. 4-1. Example of a field visual mockup showing multiple substrates and components
Source: Courtesy of Corgan Architects, Dallas; reproduced with permission

materials. Visual mockups are often erected onsite as a reference quality assurance benchmark for the contractor.

4.1.2 Performance Mockups

Performance mockups are more sophisticated than aesthetic mockups, although a performance mockup does allow the design team and ownership to obtain an aesthetic view of the wall assembly. The performance mockup may be subjected to a sequence of tests, including lateral loading (i.e., wind loading) for structural response, seismic racking, water infiltration (static and dynamic), air infiltration, thermal performance, and sound transmission. Typically, the basic tests include lateral loading, water infiltration, and air infiltration. The lateral-loading tests focus on frame movement and anchorage resistance. Water-infiltration testing ascertains the waterproofing performance of the façade. Air-infiltration testing relates primarily to building energy concerns and directly concerns both the building's mechanical HVAC systems performance and the glazed system composition.

Performance mockups are created and tested in test chambers at a manufacturer's facility or an independent laboratory. One variation is simply to perform water testing on a site-constructed mockup to check framing and material jointing and frame weepage mechanisms (Fig. 4-2).

4.2 STANDARDS RELATED TO CURTAIN WALL SYSTEMS

Several standards relate to curtain wall systems. In some cases, voluntary specifications exist as well. The main organizations that provide guidance and recommendations related to curtain wall systems include

- American Society of Testing Materials (ASTM)
- American Architectural Manufacturers Association (AAMA), (AAMA 1987, 1989)
- Aluminum Association (AA), (AA 2000)
- American Society of Civil Engineers (ASCE) (ASCE 2010)
- Glass Association of North America (GANA), (GANA 1997)
- International Code Council (ICC) (ICC 2006) and similar

Other related organizations provide information or guidelines that concern curtain wall or the glazing industry, including

- National Fenestration Rating Council (NFRC)
- National Institute of Building Sciences (NIBS)–Whole Building Design (WBD)

Fig. 4-2. Example of an installed two-story mockup for testing
Source: Courtesy of Construction Consulting International; reproduced with permission

4.2.1 Representative Standards Listing

The following listing is not comprehensive but indicates the general types of testing and the sources for some testing protocols. Other test methods are published and available that include component-specific or variable-specific testing.

ASTM Within the following listing of test standards, the **bolded** text refers to more widely used or specified test protocols:

C717-09	Terminology of Building Seals and Sealants
C864-05	Specification for Dense Elastomeric Compression Seal Gaskets, Setting Blocks, and Spacers
C920-08	**Specification for Elastomeric Joint Sealants**
C1193-09	Guide for Use of Joint Sealants
C1401-09a	Guide for Structural Sealant Glazing

E90-09	Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements
E283-04	**Test Method for Determining Rate of Air Leakage through Exterior Windows, Curtain Walls, and Doors under Specified Pressure Differences Across the Specimen**
E330-02	**Test Method for Structural Performance of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference**
E331-00	**Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference**
E547-00	Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference
E1105-00	**Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference**
E1186-03(2009)	**Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems**

AAMA

AAMA 501	**Methods of Test for Exterior Walls**
AAMA 501.4	Recommended Static Test Method for Evaluating Curtain Wall and Storefront Systems Subjected to Seismic and Wind-Induced Interstory Drifts
AAMA 501.5	Test Method for Thermal Cycling of Exterior Walls
AAMA 502-08	**Voluntary Specification for Field Testing of Newly Installed Fenestration Products**
AAMA 503	**Voluntary Specification for Field Testing of Metal Storefronts, Curtain Walls, and Sloped Glazed Systems**

Note that AAMA (1987) and AAMA (1989) provides several design guides and technical reports.

4.2.2 Typical Prevalent Standards

The more prevalent industry standards focus mainly on air- and water-resistance performance. These elements may be tested in the laboratory or in the field (on site). The more widely used tests are **ASTM E331, ASTM E1105,** and **AAMA 502**. In addition, several standards relate to the quality and performance of other curtain wall components, such as glazing, gaskets, and sealant (see the aforementioned ASTM listing of test standards) and analytical methodology.

4.3 TYPES OF TESTS

As previously noted, several types of tests are available to the industry and frequently used. This discussion focuses on the main types in common use. In general, testing can be divided into two main categories: mockup testing and component testing.

4.3.1 Mockup Testing

Mockup testing can be conducted in a controlled space such as an accredited laboratory or in the field. In the laboratory, more components can be tested than in the field because of setup and the fact that the environment is controlled within the test chamber. Elements such as deflection gauges or load cells can be strategically located to obtain data to compare with computational analysis generally performed by a registered professional on these system types. A mockup provides an excellent opportunity to observe a full-scale sample of the building façade (Fig. 4-3).

Laboratory Testing In the laboratory, the curtain wall system is installed to replicate the field connections, and the system is tested for the following performance aspects:

- Air infiltration (Fig. 4-4),
- Water infiltration (static and dynamic) (Figs. 4-5 and 4-6),
- Structural-loading response (wind, seismic) (Fig. 4-6)
- Debris impact testing (Fig. 4-10 to 4-12)

Air Infiltration Air infiltration is an important check because it indicates system tightness with respect to air flow. Air tightness is important because of the large number of units of this type to be installed on a typical high-rise building and ongoing building code demands and challenges to be energy efficient. Air infiltration also is checked on membranes used in building envelope and curtain wall construction. An example of this is shown in Fig. 4-4.

Water Infiltration Water infiltration generally is checked using a spray rack for static testing (Fig. 4-5) or a plane engine to spray water at a prescribed rate simulating a wind event for dynamic testing (Fig. 4-6). The

Fig. 4-3. Example of an installed two-story mockup for testing
Source: Courtesy of Construction Consulting International; reproduced with permission

Fig. 4-4. Air tightness test of an envelope component ASTM 1186
Source: Courtesy of Construction Consulting International; reproduced with permission

Fig. 4-5. Example of static water test on a curtain wall mockup
Source: Courtesy of Architectural Testing Inc.; reproduced with permission

test is used to check the water infiltration integrity of the framing joinery, gaskets, and sealants.

Structural Loading Structural loading refers to the effective pressure or force applied to the mockup. For lateral loading tests, this relates to wind pressure expressed from 3 s gust velocity (exerting wind pressure on the system). For seismic loading, it relates to the level of racking or in-plane translation or deformation of the curtain wall when the framing is subjected to design limits and then returns to original position. Neither case should result in failure of the curtain wall framing or glazing. For blast loading, it relates to the specified charge, standoff distances, and the load impulse.

Debris-Impact Testing Debris-impact testing is an important method for categorizing framing systems performance in various jurisdictions across the country. Hurricane effects on buildings have long been studied, but only after the significant devastation and cost impact of Hurricane Andrew in the Miami, Florida area, did Dade County (FL) adopt stringent

Fig. 4-6. Representative mockups for dynamic water testing at laboratory
Source: Courtesy of Architectural Testing Inc.; reproduced with permission

rules for glazed exterior wall systems to resist impact loading from windborne debris (Figs. 4-7 to 4-9). This requires analysis and testing for missile impact and cyclic loading and is currently required for all new curtain wall, storefront, or window systems installed in that region (Figs. 4-10 to 4-12).

Field Testing The field testing of a mockup generally is linked to an onsite assembly of multiple substrates representing the building envelope components on the project. Some components, such as masonry, natural stone, and panels (monolithic or composite) are scaled and integrated with actual size curtain wall, storefront, and glazing (Fig. 4-1). Viewing size and scale are determined by the owner or architect.

These field mockup tests serve many purposes, including

- Review of the material aesthetics prior to mass production
- Review of the material aesthetics in the onsite setting
- Observation of key interfacing components for aesthetics and construction. Often multiple trades need to coordinate efforts and

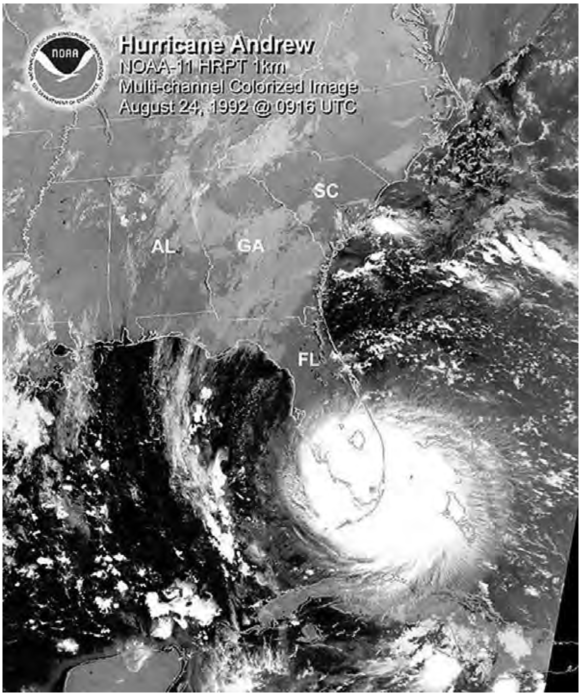

Fig. 4-7. Showing the magnitude of Hurricane Andrew in 1992
Source: http://commons.wikimedia.org/wiki/File:Hurricane_Andrew_Landfall .jpg; reproduced courtesy of NOAA

sequencing of installation; constructing a field mockup provides an excellent opportunity to work out the "kinks" prior to mass installation of the wall system

- Involvement of manufacturer's representative early with potential complex transitions and sequencing to conduct a review or demonstrate critical installation steps, products, and methods to the subcontractor; this involvement also assists in quality assurance related to manufacturer's warranties; the more sensitive elements for warranties are waterproofing elements and sealants

The actual types of tests with a field mockup can include a "box" chamber test (air or water) with a water spray rack for overall assemblies subjected to a vacuum (Figs. 4-13, 4-14 and 4-16) or a calibrated hose nozzle water test for individual components of an assembly (Fig. 4-15).

Fig. 4-8. Projectile penetrating a tree during Hurricane Andrew in 1992
Source: Courtesy of NOAA

4.3.2 Usefulness of Tests

Testing of curtain wall and related components serves a vital role in building performance. Testing is imperative if the proposed systems are prototypes, new innovations, or significantly complex, especially if the material to be installed on the project has a large square footage.

Test results demonstrate or provide early indication of expected performance and provide further opportunities to correct either the design, material choice and installation methods, or sequence prior to jobsite installation. Any needed corrections must be addressed immediately. Furthermore, maintaining continuity by using the same work crews who installed the mockup for the project installation is advisable. The critical parameter is knowledge transfer in the required installation process and also in the event of required modifications during the testing process.

One of the most important aspects of testing is documentation. A test protocol is followed, then laboratory or field results are published and can be compared with initial analytical modeling. In the case where modifications are needed for mockup success, they must be correctly documented

Fig. 4-9. Close-up of the projectile embedded in a palm tree
Source: http://www.photolib.noaa.gov/brs/nwind12.htm; courtesy of NOAA

Fig. 4-10. Example of small-frame testing: missile cannon
Source: Courtesy of Thornton Tomasetti; reproduced with permission

Fig. 4-11. Example of small-frame testing: cyclic testing
Source: Courtesy of Thornton Tomasetti; reproduced with permission

Fig. 4-12. Example of large frame curtain wall with missile (wood 2x4 stud)
Source: Courtesy of Architectural Testing Inc.; reproduced with permission

Fig. 4-13. A representative box chamber around a specimen that tests air leakage and water infiltration
Source: Courtesy of Leak Investigation and Testing Services, Inc.; reproduced with permission

Fig. 4-14. Applying a vacuum to the chamber
Source: Courtesy of Leak Investigation and Testing Services, Inc.; reproduced with permission

Fig. 4-15. A hose nozzle test AAMA 501.2
Source: Courtesy of McFarquhar Group, Inc.; reproduced with permission

Fig. 4-16. A spray rack test AAMA 503
Source: Courtesy of Construction Consulting International; reproduced with permission

and implemented in the actual job construction. The documentation is a method of record keeping but also enables the architect, consultants, general contractor, and subcontractor to observe, verify, or quantify that the modifications are being implemented on the actual project.

4.3.3 Specific Applications

Curtain wall assemblies often are integrated with multiple other substrates on a building façade. In other cases, the level of complexity is project driven and may require unique testing applications. Some examples are large skylights, sloped glazing, and truss curtain walls.

4.4 MOCKUP TESTS

Mockups are representative of the actual building profile and usually encompass the typical areas. Because all buildings have some level of sophistication or uniqueness, the owner or design professional typically is responsible for deciding what area and scope to test in the mockup. As previously stated, different mockup tests address specific features.

The wind tunnel test is useful during the project design and construction documents phase of a project. The information provided includes the expected wind flow characteristics on the project building. Prior to construction, mockups are tested in the laboratory, and during construction they are tested in the field.

4.4.1 Wind Tunnel Tests

Wind tunnel studies are a unique application of science and modeling based on the building profile, location, and surrounding conditions. The test building is a small-scale model at a scale of about 400 : 1 with pressure taps and includes surrounding area buildings and landscape (Fig. 4-17). Including surrounding conditions is important because of a parameter termed the roughness coefficient, which is a numerical value to simulate the existing surface boundary conditions (e.g, urban,wooded area, open grassland, coastal areas) for the project building. The model is placed on a table that rotates, thus allowing data to be collected from different angles. ASCE 7-10 (ASCE 2010) defines relative building locations in categories termed exposure A through D. This exposure factor, along with the global location, affects the governing parameters describing the expected wind pressure on the building in intensity and magnitude.

Wind tunnel testing (Figs. 4-18 and 4-19) offers a significant advantage by simulating the effect of wind on a structure prior to its construction and can highlight special areas on the building profile that are highly affected by wind, called “hot spots.” This modeling and testing application provides information about

- Building envelope cladding pressures,
- Roof pressures,
- Building dynamics (such as base shear and overturning moment),

Fig. 4-17. Scaled building model in wind tunnel test
Source: Courtesy of CPP, Inc.; reproduced with permission

Fig. 4-18. Wind tunnel testing
Source: Courtesy of CPP, Inc.; reproduced with permission

- Pedestrian level study related to magnitudes of gusts at the sidewalk and the front entry areas, and
- Air flow simulation studies by smoke flow (useful with dispersants studies; to observe the effects of exhaust from the building and

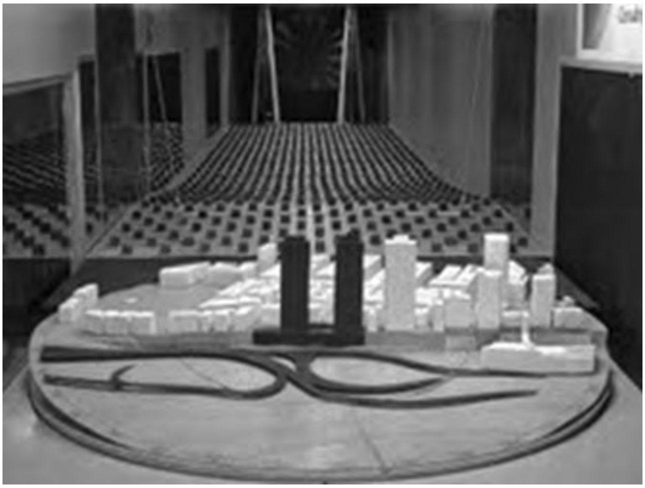

Fig. 4-19. Wind tunnel testing
Source: Courtesy of Rowan Williams Davies & Irwin; reproduced with permission

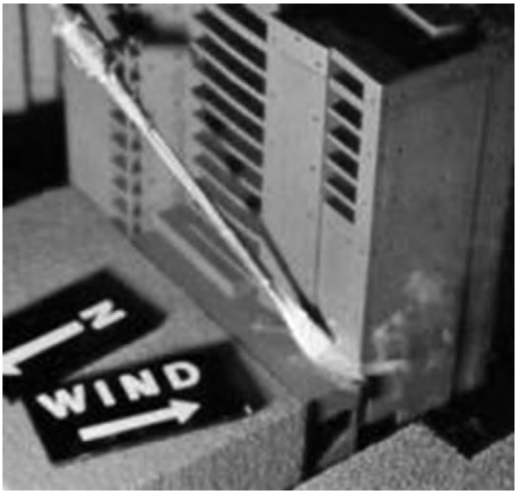

Fig. 4-20. Representative wind dispersion study using smoke
Source: Courtesy of CPP Inc.; reproduced with permission

negate adverse effects to the building façade or occupants prior to construction, Fig. 4-20).

The information developed from these parametric studies especially on the effects of wind velocity direction and the resulting pressures is useful to design professionals in determining system types and special conditions to be addressed.

Note that the design wind pressure is a function of geographical location. It varies across the country and the building geometry also contributes to the resulting design parameter. Curtain wall–expected wind pressures on the coastal areas, especially in the Southeast and Gulf of Mexico areas, are significantly higher than in areas in the Midwest for the same building height.

4.4.2 Laboratory Tests

As previously discussed, laboratory testing is quite involved and requires a lot of planning by the architect selecting the scope to be tested and the subcontractor procuring the material to facilitate the test. The curtain wall framing assembly and the actual vertical anchor connections are installed for testing. Often some modification of head and sill anchorage occurs depending on the test chamber or to compare project-supporting substrates such as concrete or steel. The curtain wall is usually tested for air and water infiltration up to design pressure and for structural integrity response to 150% design wind without permanent damage to the framing.

4.4.3 Field Tests

One important advantage of field tests is the ability to conduct them at various stages of the project: early, middle, and 75% of construction. In addition, the tests can be repeated and can take place anywhere on the façade, provided the logistics are not too cumbersome for rigging of equipment, or other activities. Field tests are in-situ testing of the actual assemblies and provide qualitative assessment of not only consistency in installation but also system performance.

4.5 OBSERVATIONS

The importance of project observations cannot be overstated. Observation sequences may occur pre- or postinstallation of the curtain wall. The primary purposes are to review the following aspects:

- Conformance with the project construction document requirements,
- Consistency in the installation,
- Quantified levels of installation for contractor scope payment,
- Problem solving for field conditions, and
- Punch lists.

Observations are generally conducted by an owner's representative, architect, cladding consultant, manufacturer's representative, subcontractor, or general contractor. Depending on the nature of the review, reports with representative photographs are generated along with punch lists. Early observation is highly recommended because it provides an opportunity for the construction team to make adjustments or corrections within the early stages of a project and avoid compounded problems at the end of the project.

As previously mentioned, opportunities exist for pre- and post-observations. Pre-observations include reviews at a laboratory (testing), onsite mockups (testing or visual), and reviews of the manufacturer's plant or fabricator facilities (visual or occasional testing depending on the capability of the facility). Post-observations include observations of onsite progress installation and construction of the curtain wall.

4.5.1 Mockup Observations

A preinstallation mockup (lab or field) is an invaluable tool or mechanism to allow the owner or architect to review a representative scaled section of the project for both aesthetics and performance. Elements related to color choices and material finishes may be reviewed prior to bulk ordering and installation in the field. The contractor and subcontractor benefit as well from assessing the level of expertise and efficiency required to install the mockup, further allowing special concerns or observed problems to be corrected prior to installation on the project.

Based on testing results, all parties, including the owner, design team, contractor, and subcontractor, can confirm that the curtain wall system meets their performance expectations and complies with the project specifications.

4.5.2 Factory/Fabricator Observations

Conducting observations at the curtain wall manufacturer plant, such as an extrusion plant or at the fabricator facility, is always advisable (Figs. 4-21 and 4-22). Important elements include the production capacity, cleanliness of facility (especially where sealant work is being conducted), quality assurance protocols, quality checks, random batch sampling, tooling capabilities, staff, and shipping facilities. All these elements are important during the process of manufacturing and fabrication to the design specifications of approved shop drawings and company methods. What makes curtain wall systems so unique is the ability to extrude multiple shapes from aluminum and assemble these shapes as needed for differing performance and function.

Fig. 4-21. Frame assembly
Source: Courtesy of Oldcastle BuildingEnvelope®; reproduced with permission

Fig. 4-22. Frame storage and handling
Source: Courtesy of Oldcastle BuildingEnvelope®; reproduced with permission

4.5.3 Site Observations

Site observations offer the opportunity not only to witness performance of tested assemblies but also to observe the construction or installation of the assembly prior to testing. Elements such as damaged framing;

damaged glazing; poor sealant tooling; and inadequately installed gaskets, frame joinery, and frame anchorage or connections are important issues that affect the performance of the curtain wall system. Site observations should begin at the onset of construction and continue throughout the process. Deficiencies or punch list items should be documented, and any corrective measures (if needed) for field testing be implemented in the field installation practice.

4.5.4 Storage Observations

Storage observations are a part of the site observations but focus on how well stored material is protected or on the mechanism of storage. Bundled framing in crates will require tarps or other appropriate methods to keep dust off the stored units or avoid damage to the metal finish or glazed components. If the frames are stacked vertically or horizontally, they need to be separated with insulating material to protect the metal finish. The significance of proper protection is to ensure that the product, when installed, will be free from unnecessary damage or displacement resulting from high traffic in jobsites where multiple trades are performing their respective tasks.

4.5.5 Documentation

The importance of documentation is self-explanatory because there needs to be design intent directive, contractors shop drawings and analysis that interpret that design intent with a specific curtain wall system, and field observations showing compliance or non compliance with the contract documents. All parties involved with the project document their work. Several tools are available, such as photography (regular and thermographic), video, and laptops and scanners, which allow a tremendous amount of data to be quickly processed, transmitted or filed. Ultimately, the individual determines how this information is disseminated in office filing or reports. One thing, however, is always certain: The best defense is good documentation, whether it occurs before, during, or after testing.

4.6 SUMMARY

Testing has many facets, but it is an integral part of the performance assessment of curtain wall, storefront, and window-wall systems. It provides a mechanism for system designers and manufacturers to improve their product and provides a comfort level to the owners and architectural design team (architects and consultants) as well as the general contractor and subcontractors that the product performs as required. The quantity, scope, and budget for testing is project specific, but mockups and testing are highly recommended for in projects where issues can be addressed early before mass installation on the building.

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CHAPTER 5

DESIGN OF CURTAIN WALLS FOR ENERGY PERFORMANCE

Faron A. Morris

Heat transfer across curtain wall occurs by three mechanisms: conduction, convection, and radiation (Straube and Burnett 2005). Conductive heat transfer occurs through a solid material or through individual materials in direct contact with one another and is determined by the material's conductivity. For example, the interior surface of an aluminum mullion without thermal separation will feel cold in winter because heat is drawn through the member from the interior to the exterior by conduction. Heat flows from high temperature to low. Thus, the mullion feels cold because the cold exterior is drawing heat through the mullion wall via conduction. Cold framing members can lead to condensation, an undesirable result discussed later in this chapter. A mullion designed for high thermal performance would feel warm in winter.

Convection occurs through the flow of air either by forced air movement or by currents of warm heated air rising and cool air falling, known as natural convection. Wind is an example of forced air convection that, in the presence of radiative heating, has the effect of decreasing surface temperatures to as low as ambient air temperature. Air movement draws heat from the surface of an object; the rate of heat loss depends on the material's surface film coefficient and air velocity.

Radiation is heat transfer by electromagnetic radiation through an air space. The heat felt from a hot stove is an example of radiation. All components of a curtain wall emit radiation called long-wave infrared radiation. Radiation occurs across bands of wavelengths grouped in spectra. The thermal radiation frequency emitted by an object depends on the object's surface temperature. The sun's surface is extremely hot compared to Earth with short-wave infrared (also known as solar infrared) radiation being the sun's primary source of heat. Terrestrial or Earth-based objects such as construction materials, including curtain wall, will absorb this short-wave infrared, increase in temperature, as seen on a hot summer day, then re-radiate heat in the form of long-wave infrared radiation. Long-wave radiation possesses less energy than short-wave radiation because the wall's surface temperature is much lower than the sun's surface temperature. Glass will absorb, transmit, and reflect radiation at a given frequency in a ratio given by absorptance + transmittance + reflectance = 1.0. Opaque materials do not transmit radiation, therefore the relationship is absorptance + reflectance = 1.0. In the long-wave infrared spectrum, a material's absorptance equals its emissivity, a property that describes its ability to re-radiate long-wave infrared radiation. Absorptance, transmittance, reflectance, and emittance are unitless ratios between zero and one. For example, plain glass has an emissivity of 0.84 in the long-wave infrared spectrum, which means it absorbs 84% of incident radiation in this spectrum but also radiates 84% of the radiation it can emit based on its temperature. Glass does not transmit long-wave radiation, therefore 16% is reflected. For comparison, most building materials, such as wood, plastics, insulation, and painted metals, have an emissivity of about 0.9. Shiny metals, such as mill aluminum and buffed stainless steel, have an emissivity of about 0.2. Low-e coatings on glass can be as low as 0.02 and lower.

5.1 HEAT LOSS ACROSS CURTAIN WALL

Controlling heat flow across curtain wall can be separated into three design objectives: (1) controlling heat loss from the interior in heating-dominant climates, (2) controlling heat gain from the exterior in cooling-dominant climates, and (3) air leakage control. Excessive heat loss in winter increases heating energy costs and occupant discomfort at the building periphery. Heat loss coincides with interior aluminum framing surfaces becoming colder, leading to condensation on interior surfaces under the right conditions. Condensation is moisture accumulating on cold surfaces that drop below the dew point temperature of the interior air, which depends on room temperature and relative humidity. Dew point temperatures can be obtained from psychrometric charts. Indoor condensation can lead to mold with related health issues, stain and damage interior finishes, such as drywall and ceiling tiles, and cause corrosion in metals not intended to be wet. Heat loss is controlled by vision glazing through the use of double- or triple-glazed insulating glass units (IGU), gas fills such as argon, low-e coatings, thermal spacers, insulation in spandrel openings, and thermal separation of aluminum framing members.

Excessive heat gain in summer also increases cooling energy costs to maintain a desirable interior temperature. Occupant discomfort also

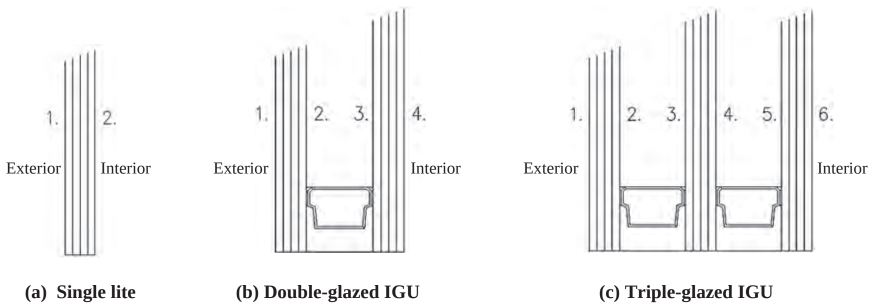

Fig. 5-1. Numbering convention of glazing surfaces
Source: Author drawing

occurs at the building periphery where heat gain is the highest within the floor plan. Thermostat controls are generally located at mid-floor plan to reduce the influence of higher temperature fluctuations at the periphery. Heat gain is controlled by the use of double- or triple-glazed IGUs, low-e coatings, reflective coatings, tinting, opaque spandrel openings, and sunshades. The numbering convention when referring to glazing surfaces is shown in Fig. 5-1. Numbering starts on the outboard surface proceeding inward on each face. For example, low-e coatings to control solar heat gain are placed on surface no. 2 in double-glazed IGUs. In Fig. 5-1b surface no. 2 is the inboard face of the outboard lite.

5.2 U-VALUE: DETERMINING HEAT LOSS

Determining heat loss requires area weighting three components of a curtain wall opening: the center of glass (cog), the edge of glass (eog), and the frame (GANA 2009). Once area weighting has been done for all openings in a given wall area, the individual openings can together be area weighted to obtain an overall u-value for a wall area. U-value is a measure of heat loss (watts) for a given wall area (square meters) for a given temperature differential (Celsius) under fixed environmental conditions consisting of indoor air temperature, outdoor air temperature, and outdoor wind speed. Units for u-value are W/m^2-°C with a lower u-value indicating better curtain wall performance due to lower heat loss through the wall assembly.

The largest and most influential component of the three is the cog. The cog is readily published by glass suppliers and often confused with the overall vision u-value. The overall u-value is determined by area weighting u-values from each of the three components for each opening in the wall. These openings often repeat, which can be used to advantage by reducing the number of unique openings and thus simplifying the overall u-value calculation. The design of a new tower, when sizing HVAC equipment, must make use of the overall u-value and not the cog u-value. As shown in the following example, this can make a significant difference. The second component is the eog, comprising 63.5 mm of the glazing infill from the edge or side of framing. The calculation for cog is a one-dimensional heat transfer problem. But heat transfer across the frame and eog is two-dimensional. This 63.5 mm standard distance defines the cutoff between one- and two-dimensional heat flow. The third component is the frame, where heat loss through conduction dominates because of the use of highly conductive aluminum. For larger opening sizes the relatively small frame area offsets the high frame u-value. Frame boundaries, where the dividing line is chosen between adjacent openings, must be chosen carefully. Defining openings that are repetitive and do not overlap or leave out any area over which the overall u-value is to be determined is necessary. The dividing line between framing members often is best chosen as the member center line but can be any other convenient point provided all portions of the overall area are modeled. As will be discussed later, two separate computer programs are used to determine cog, eog, and frame u-values.

Fig. 5-2 shows two vision openings from a curtain wall elevation, one square and one rectangular consisting of a structural silicone glazed (SSG)

Fig. 5-2. Example vision openings: (left) 1200 mm × 1200 mm vision opening; (right) 1500 mm × 2750 mm vision opening
Source: Sota Glazing, Inc.

6 mm + 6 mm IGU with low-e coating (0.088 emissivity) on no. 2 surface, 12.7 mm air space, standard aluminum spacer, and 3 × 5.75 in. aluminum frame with a commercially available, glass fiber–reinforced nylon 12 mm thermal break. Each opening has one cog, four eogs, and four frame members, the areas and u-values of which must be determined. The breakdown of the individual areas and u-values are listed in Tables 5-1 and 5-2, which show that cog area increases significantly with opening size in comparison with eog and frame areas. In Table 5-1 the cog area is 68.1% of the total frame area, and in Table 5-2, the large opening, the cog area increases to 79.3%. Generally the cog u-value is the lowest (least heat loss) of the three components followed by eog then frame members. Framing members are the biggest source of heat loss in curtain walls, which makes the strategy of creating bigger opening sizes on a project worthwhile. This has the effect of increasing cog area, the best-performing thermal component, while reducing glass edge and frame heat loss effects. When modeling framing members, continuity of the wall is assumed because the frame opening repeats in all directions. In that case the framing members will have vision glass on each side to model heat transfer effects accurately while obtaining the u-value from the member centerline to the edge at glazing. However, sometimes the adjacent side of the framing member is a spandrel opening instead of a vision opening. The mullion would then be modeled with spandrel on one side and vision on the other, but the frame u-value would be taken to the mullion centerline for the vision opening frame u-value.

The ratio of frame area drops from 13.3% in Table 5-1 to 8.5% in Table 5-2 providing an overall u-value decrease of 9.2% from 2.39 W/m^2-°C to 2.17 W/m^2-°C. This represents a 9.2% performance gain simply by increasing the opening size, which also increases the cog area. With each of the two openings consisting of identical component u-values, the area weighting effect makes the larger opening the better thermal performer.

The area weighting calculation is relatively straightforward. Multiply each component u-value with its corresponding area for each member in the opening, sum them, then divide that total by the total area for the overall opening u-value:

$$U_{overall\ opening} = (U_{cog} \times A_{cog} + U_{frame1} \times A_{frame1} + U_{edge1} \times A_{edge1} + \ldots + U_{frame\ n} \times A_{frame\ n} + U_{edge\ n} \times A_{edge\ n}) / A_{opening} \quad (5\text{-}1)$$

where n is the total number of members in the opening, in this case four: a header, a sill, and two mullions.

Optionally, determine the fraction of the total area of each component, multiply that fraction by each component's u-value, then sum them for each member to obtain the overall opening u-value:

Table 5-1. Overall U-Value Calculation for a 1.2 m × 1.2 m Vision Opening

Overall U-Value Calculation				1200 mm × 1200 mm	
No.	Member	Area (m²)	Fraction of Total	U-Value (W/m²-°C)	A × U (W/°C)
1	Center of Glazing	**0.981**	0.681	**1.75**	1.72
	Sum	**0.981**	**0.681**		**1.72**
		Edge			
2	Head	**0.067**	0.046	**1.74**	0.12
3	Mullion Left	**0.067**	0.046	**1.83**	0.12
4	Mullion Right	**0.067**	0.046	**1.83**	0.12
5	Sill	**0.067**	0.046	**1.74**	0.12
	Sum	**0.268**	**0.186**		**0.48**
		Frame			
2	Head	**0.044**	0.031	**6.14**	0.27
3	Mullion Left	**0.052**	0.036	**6.80**	0.35
4	Mullion Right	**0.052**	0.036	**6.80**	0.35
5	Sill	**0.044**	0.031	**6.14**	0.27
	Sum	**0.192**	**0.133**		**1.25**
			Total Area =	1.44 m²	
			Total Fraction =	1.000	
			Overall U-Value =	**2.39 W/m²-°C)**	

$$U_{overall\ opening} = (U_{cog} \times Fraction_{cog} + U_{frame1} \times Fraction_{frame1} + U_{edge1} \times Fraction_{edge1} + \ldots + U_{frame\ n} \times Fraction_{frame\ n} + U_{edge\ n} \times A_{edge\ n}) \tag{5-2}$$

where n is the total number of members in the opening, in this case four, and $Fraction_n = A_n/A_{opening}$.

The total area $A_{opening} = A_{cog} + (A_{frame1} + A_{frame2} + A_{frame3} + A_{frame4}) + (A_{edge1} + A_{edge2} + A_{edge3} + A_{edge4})$.

The 6 mm clear + 6 mm clear IGU with low-e coating (0.088 emissivity) in the aforementioned example is a commonly used vision infill. Improved thermal performance can be achieved by any of the following infill changes, either individually or in combination: triple-glazed unit, increased lite thickness, argon air space gas fill, and improved low-e coating (tints do not affect heat loss). Table 5-3 provides cog u-values for

Table 5-2. Overall U-Value Calculation for a 1.5 m × 2.75 m Vision Opening

Overall U-Value Calculation				1500 mm × 2750 mm	
No.	Member	Area (m²)	Fraction of Total	U-Value (W/m²-°C)	A × U (W/°C)
1	Center of Glazing	**3.270**	0.793	**1.75**	5.73
	Sum	**3.270**	**0.793**		**5.73**
		Edge			
2	Head	**0.086**	0.021	**1.74**	0.15
3	Mullion Left	**0.166**	0.040	**1.83**	0.30
4	Mullion Right	**0.166**	0.040	**1.83**	0.30
5	Sill	**0.086**	0.021	**1.74**	0.15
	Sum	**0.504**	**0.122**		**0.91**
		Frame			
2	Head	**0.055**	0.013	**6.14**	0.34
3	Mullion Left	**0.121**	0.029	**6.80**	0.82
4	Mullion Right	**0.121**	0.029	**6.80**	0.82
5	Sill	**0.055**	0.013	**6.14**	0.34
	Sum	**0.352**	**0.085**		**2.32**
			Total Area =	4.13 m²	
			Total Fraction =	1.000	
			Overall U-Value =	**2.17 W/m²-°C)**	

Note: SHGC refers to solar heat gain coefficient and VT refers to visible transmittance. R-value is the inverse of u-value.

given glazing thermal performance modifications and the percentage change from the base makeup no. 1. The IGU from the two aforementioned examples is makeup no. 6. Tinted glass has metals and metal oxides added during the manufacturing process to give it color. Tinting has no effect on heat loss (u-value), but it can improve solar heat gain. Common tints are bronze, green, gray, and blue.

Opaque spandrel areas offer more opportunities to increase thermal performance through the addition of insulation. Spandrel openings perform significantly better thermally than vision openings.

For a given curtain wall project for which the u-value is required to be determined, varying opening sizes of vision and spandrel are likely to occur. Simply tabulate and calculate the u-value for each of the individual sizes then area weight again for an elevation or an entire project. The

Table 5-3. Makeups to Indicate Optical, Thermal, and Solar Effects

Makeup No.	Name	U-value Metric (W/m²-°C)	% *Difference* —	R-value Metric (m²-°C/W)	SHGC —	% *Difference* —	VT —	% *Difference* —
1	Clear	5.8	*116*	0.17	0.82	*16*	0.88	*12*
2	Clear + Clear	2.7	*0*	0.37	0.70	*0*	0.79	*0*
3	Green Tint + Clear	2.7	*0*	0.37	0.47	*–32*	0.67	*–14*
4	Reflective Coating + Clear	2.4	*–10*	0.41	0.24	*–65*	0.18	*–77*
5	Low-e 0.206 + Clear	2.0	*–27*	0.51	0.51	*–28*	0.61	*–22*
6	Low-e 0.088 + Clear	1.8	*–35*	0.57	0.54	*–22*	0.76	*–4*
7	Low-e 0.018 + Clear	1.6	*–40*	0.62	0.27	*–61*	0.64	*–19*
8	Clear + Low-e 0.018	1.6	*–40*	0.62	0.37	*–47*	0.64	*–19*
9	Low-e 0.018 + Clear w/Argon	1.3	*–50*	0.74	0.27	*–61*	0.64	*–19*
10	Reflective + Low-e 0.018	1.6	*–40*	0.62	0.14	*–80*	0.15	*–81*
11	Clear + Clear + Clear	1.7	*–35*	0.57	0.61	*–12*	0.70	*–11*
12	Low-e 0.018 + Clear + Low-e 0.018	0.9	*–65*	1.07	0.22	*–68*	0.46	*–41*
13	Low-e 0.018 + Clear + Low-e 0.018 w/Argon	0.8	*–70*	1.24	0.22	*–68*	0.46	*–41*

procedure is identical to the u-value calculation discussed previously. Individual openings are area weighted against the elevation or project area they cover.

Knowing that spandrel openings are thermally better than vision openings, another simple strategy for improving overall thermal performance is to increase spandrel area and reduce vision area. This is very effective with big potential gains in overall wall u-value. For example, the vision opening in Table 5-2 with 2.17 W/m^2-°C overall u-value and 70% elevation coverage and a spandrel opening with 1.10 W/m^2-°C overall u-value and 30% coverage provides an overall elevation u-value of 0.70×2.17 W/m^2-°C $+ 0.30 \times 1.10$ W/m^2-°C $= 1.85$ W/m^2-°C. By reversing the vision and spandrel proportions the new u-value becomes 0.70×1.10 W/m^2-°C $+ 0.30 \times 2.17$ W/m^2-°C $= 1.42$ W/m^2-°C, a decrease (thermal performance improvement) of 23% in overall elevation u-value.

5.3 HEAT GAIN AND SOLAR RADIATION

Heat gain through curtain wall originates from solar radiation from the sun. Solar radiation has three components: ultraviolet, visible, and thermal or infrared radiation. The solar spectrum consists of 2% ultraviolet, 47% visible, and 51% infrared. The human eye does not see ultraviolet wavelengths, which are responsible for fading indoor materials and deterioration of some plastics. Visible wavelengths are visible to the human eye and desirable for lighting of interior spaces. The main appeal of glazing is its ability to transmit visible light. Solar infrared is not seen by the human eye either, but it can be felt in the form of heat. It is also referred to as near-infrared or shortwave radiation because of the high surface temperature of the object emitting it, the sun. The higher the source object's surface temperature, the shorter the wavelength and higher the energy intensity of the emitted radiation. The surface temperatures experienced by curtain wall and construction materials are significantly lower than the surface of the sun. These Earth-based (terrestrial) surfaces also emit thermal (infrared) radiation but at a longer wavelength referred to as long-wave infrared radiation, or terrestrial radiation. An object brought out into the sun is heated by the sun's near infrared (short-wave) radiation, raising the object's temperature. The object re-radiates far infrared (long-wave) radiation based on its emittance – a property of the material. The higher the emittance, the more it re-radiates the sun's heat it has absorbed, reducing its surface temperature. The lower the object's emittance, the less it radiates heat, increasing its surface temperature. Emissivity is a term used to describe the ability of a surface to reflect infrared radiation. Polished metals are materials with low emissivity (low-e) surfaces, whereas dark and dull surfaces generally have high emissivity surfaces. Thus, thin layers of tiny metal particles can be applied to glass to create low-e coatings beneficial in reducing outdoor solar heat gain in summer and indoor thermal heat loss in winter.

Another method of reducing heat gain other than low-e coatings is by physically blocking solar radiation from reaching the glazing. Sunshades are effective when used on the outside of the curtain wall. In contrast, little benefit is gained by placing shading devices such as blinds on the inside of the wall to control heat gain because solar radiation is absorbed then re-radiated to the interior space. Deciduous trees are used in a similar manner to sunshades in residential areas by locating them to shade window openings, where heat gain is the highest in summer; then in winter when their leaves fall off solar heat gain contributes to the heating requirements as passive or free heating from the sun.

5.4 GLAZING OPTIONS FOR THERMAL PERFORMANCE

Curtain wall with glazing that fails to reduce solar heat gain permits incident solar radiation to transmit through the glazing and heat indoor surfaces, which rise in temperature and emit long-wave radiation. This increases indoor temperatures and simultaneously increases HVAC cooling loads in summer. In winter, passive heating, intentionally allowing solar radiation through the glazing, can be used to advantage in heating-dominated climates.

Controlling heat gain with glazing is achieved with tinted glass, reflective coatings, and low-e coatings. Tinting of glass is achieved by chemically altering the glass composition by adding metals and metal oxides. Tinted glass absorbs more solar radiation than clear glass but without a low-e coating will heat the inboard lite through infrared radiation, which in turn radiates to the interior space. Tinted glass is usually not a preferred method of reducing solar gains, because high proportions of visible wavelengths are blocked, thus reducing desirable visible light transmittance. Low-e coatings are better suited for glazing, because they can block the solar infrared wavelengths with less effect on visible transmittance. Reflective or metallic mirror coatings can be applied that reflect most wavelengths of solar radiation, but the main drawback remains insufficient visible light transmittance. The newest technology in metallic coatings is thin layers of metallic particles called low-e coatings. The level of sophistication of these coatings is such that all wavelengths can be efficiently reflected or absorbed while still allowing visible light transmittance. These are called spectrally selective coatings, or low solar gain coatings. Non-spectrally selective coatings allow transmittance of visible and infrared solar radiation, providing passive solar heating in heating-dominated climates.

5.5 SHGC: DETERMINING HEAT GAIN

Solar heat gain pertains to the infrared portion of the spectrum emitted by the sun that contributes to heating of indoor spaces. Higher-performing curtain wall can reduce the amount of solar heat gain that enters the interior space by the use of tinted and low-e coated glazing and by thermal separation of aluminum framing. Vision openings are the main source of heat gain because of the transparent properties of glazing. Spandrel openings are opaque by definition and therefore are not a significant contributor to solar heat gain.

The measure of a curtain wall's performance against solar heat gain is the solar heat gain coefficient (SHGC). SHGC is a unitless ratio between zero and one, with zero indicating no heat gain and one indicating all incident solar radiation contributes to heating the indoor space. A wall's SHGC can be determined by full-scale laboratory testing or by computer simulation.

The overall curtain wall SHGC has two components: glazing and framing. Glazing permits indoor heat gain through direct transmission, absorption and re-radiation, and convection. The portion not transferred to the interior either is reflected back outdoors or absorbed and re-radiated outdoors. Framing is opaque and therefore cannot transmit solar radiation but can contribute to indoor heating through absorption and re-radiation and convection.

When determining the overall SHGC, the same area weighting procedure that was used for u-value applies. The difference is that SHGC for cog is identical to eog because of the one-dimensional nature of heat gain across the glazing.

5.6 OPTICAL, SOLAR, AND THERMAL PERFORMANCE OF GLAZING

It is useful to understand the relationships among three values used in the selection of glazing for thermal performance and how changing one affects the others (Viracon 2008). Visible transmittance, solar heat gain, and heat loss (u-value) are the three primary criteria in the selection of glazing. The glazing makeups shown in Table 5-3 are commercially available at the time of this publication and were selected to provide comparisons of how optical, solar, and thermal performance of glazing is affected. All makeups in Table 5-3 consist of clear 6 mm lites unless indicated with a tint, reflective, or low-e coating, which is always located on the air space side of the lite. All units consist of a 12.7 mm air space unless argon gas fill is indicated. The percent difference is based on makeup no. 2, a 6 mm clear + 6 mm clear IGU, a common thickness makeup, without coatings, tint, or argon gas fill, which was selected to show the relative effect of each performance change. Metric u-values can be converted to imperial by dividing by 5.678, that is, 1 BTU/hr-ft^2-°F = 5.678 W/m^2-°C. R-value is the inverse of u-value.

A single 6 mm lite transmits 88% of visible light as indicated by makeup no. 1 (Table 5.3), and a double 6 mm unit transmits 70% of visible light. Tinted glass causes no change to u-value but decreases the SHGC owing to solar infrared absorption with a corresponding reduction in visible transmittance (VT) as indicated in makeup no. 3. Tinting is not the most effective method to reduce solar heat gain, because the emissivity of the glass is unchanged. The absorbed solar radiation, which increases the glass temperature, is allowed to re-radiate to the interior, because uncoated glass has a high emissivity (e = 0.84). A reflective coating in makeup no. 4 is more effective at reducing SHGC than tinting, because solar infrared radiation is reflected away from the interior by the metallic coating, reducing absorption and re-radiation to the interior. But the tradeoff is a significant reduction in visible transmittance. A slight reduction in u-value is because of the reduction in coating emissivity to 0.557 from 0.84 glass. Low-e coatings are effective at reducing u-value while allowing higher visible transmittance levels. Low-e coatings do not generally change the appearance of glass, making them difficult to detect by visual inspection. Makeups 5, 6, and 7 are examples of low-e coatings with varying emittances ranging from about 0.20 down to 0.02.

Emissivity directly relates to a unit's u-value—the lower the coating emissivity, the lower the glazing u-value with all else being equal. Low-e coatings are unique materials, because emissivity varies over the UV, visible, and solar infrared spectrums and can be modified to block certain spectra while transmitting others. A high solar heat gain coating as in makeups no. 5 and no. 6 has high VT (visible spectrum) and high SHGC (solar infrared spectrum) sometimes preferred in heating-dominated climates to take advantage of passive solar heating, which can provide overall yearly energy savings. A spectrally selective coating has high VT and low SHGC preferred in cooling-dominated climates as in makeup no. 7. Again, u-value decreases with decreasing coating emissivity even when the low-e coating is on the third surface as seen in makeup no. 8, which is the reverse of makeup no. 7. The drop in SHGC results from the low-e coating placement moving to surface 3, allowing more solar radiation to reach the inboard lite to re-radiate to the interior. This is a form of passive heating beneficial in cold climates. Replacing air with argon in the air space has the effect of reducing convective heat losses due to the lower density of argon gas compared with air. In makeup no. 9, a further 10% gain in u-value is achieved with no change in SHGC and VT. Makeup no. 10 provides the lowest SHGC of all the combinations listed by using a reflective coating on the outboard lite and a low-e coating on the inboard lite. The tradeoff is also the lowest VT of all the combinations listed, which negates the benefit of natural lighting gained from using glazing. U-value is unchanged from no. 8 as the reflective coating has no effect on u-value. Triple glazing allows further gains in u-value through the use of dual low-e coatings and argon gas fill. Makeup no. 11 is nearly identical in u-value to the dual IGU with low-e in makeup no. 6. Adding a low-e coating to a double-glazed IGU is thermally comparable to a triple-glazed IGU. Makeups no. 12 and no. 13 make significant improvements in u-value because of the presence of double low-e coatings, providing the second lowest SHGC. The decrease in VT is the third highest but is far less than the performance gains from u-value and SHGC—nonetheless a tradeoff to consider.

The makeups in Table 5-3 are only one example of each step in glazing performance. Numerous combinations of units and makeups are available from glazing manufacturers with variations in VT, SHGC, and tint. A spectrally selective low-e coating with given emissivity can have several VT levels with and without tints. Each manufacturer's line of low-e coatings has its own transmittance and reflectance over the three radiation spectra, which affects performance. For project-specific glazing requirements a glazing manufacturer should be consulted to narrow the choice of available products. Knowing the relationships among u-value, SHGC, and VT will help in the selection of the optimum glazing makeup on the basis of the priorities of the project and help to understand the tradeoffs that accompany the available glazing options.

5.7 AIR INFILTRATION

Air infiltration is not always understood as a source of heat loss or gain, because it is not one of the heat-transfer mechanisms of conduction, convection, or radiation. However, air leakage of conditioned interior air is a source of energy loss. The conditioned air required energy input from the mechanical system to cool or heat it depending on the climate and season. Loss of that conditioned air through cladding leakage requires sooner replacement of that lost conditioned air to maintain desired interior conditions. A leaky curtain wall can be compared to a leaky faucet, the water dripping down the drain a small but constant loss added to the household water bill.

If small openings in curtain wall are present, air leakage flow is driven by pressure differentials across the wall created by the mechanical system, stack effect, and pressure differentials from external wind pressure. A tight curtain wall prevents energy loss due to air infiltration. An air-tight curtain wall is created by sealing joints between adjacent materials and framing members. Proper detailing of project shop drawings is important as is the workmanship of the sealant applicators in the shop during glazing and assembly. Perfect air tightness is not practically achievable, so an upper limit is specified for mockup performance testing or field testing.

5.8 CONDENSATION RESISTANCE

Indoor condensation on curtain wall occurs when surface temperatures drop below the dew point temperature of the indoor air, which is based on air temperature and relative humidity. Dew point (DP) temperatures for a range of air temperatures and humidity levels are plotted on a psychrometric chart (Fig. 5-3).

The condensation referred to here is that which appears on interior surfaces of the air or vapor barrier, inside the building, and can lead to indoor performance issues resulting from mold, staining, and corrosion. Condensation on the exterior of the air or vapor barrier, outside the building, does not affect the indoor environment.

Northern, heating-dominated climates increase the importance of condensation in the design of a curtain wall system where outdoor design temperatures can range from –15 °C to –30 °C. Condensation also can

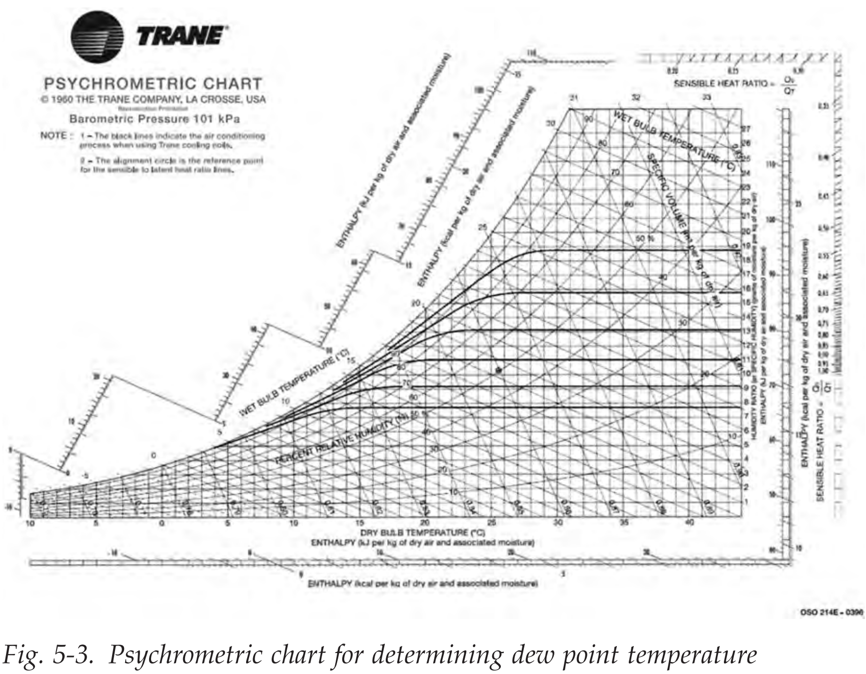

Fig. 5-3. Psychrometric chart for determining dew point temperature
Source: Courtesy of Trane and Ingersoll-Rand

occur on indoor surfaces in hot climates with high outdoor humidity through air infiltration. Interior surface temperatures are relatively low because of a conditioned space that is being cooled. Hot and humid outdoor air contacting a cool interior surface can cause condensation. Under these conditions, interior surfaces temperatures can be below the DP temperature of hot and humid infiltrating outdoor air.

Surface temperatures can be determined and condensation assessed by two methods: mockup testing and computer thermal modeling. Mockup testing for condensation is usually one of the tests performed during mockup performance testing. The conditions at which condensation is to be determined are specified at the time the project is tendered. For example, a project in a heating-dominated climate may require no condensation on interior surfaces at an outdoor temperature of –15 °C, indoor temperature of +22 °C, and indoor relative humidity of 25%. Condensation performance (in this case no condensation) is to be met at these conditions. The corresponding dew point temperature from Fig. 5-3 is 1.1 °C. Thermal modeling of framing members also can be performed to determine surface temperatures that drop below 1.1 °C under the specified project conditions. Where condensation occurs, the framing or glazing can be thermally improved to prevent condensation.

Center of glass temperatures rarely drop below the DP temperature. Section 5.2 indicated that cog glazing has the best resistance to heat loss of the three frame opening components; therefore, indoor surface temperatures at cog will be relatively high. Conductive heat loss of framing members and surface temperature generally have an inverse relationship: the higher the conductive heat loss, the lower (colder) the surface temperature. Framing members and eog are the highest heat loss (u-value) components because of the high conductivity of aluminum framing members. Conductive heat loss governs these components. As a result, condensation, if any, generally will occur on framing members and eog.

The same thermal improvements applied to framing and eog u-values also can be applied to improve condensation resistance. Wider thermal separation of member inboard and outboard extrusions using nylon thermal breaks reduces conductive heat loss. Substituting a warm edge spacer for an aluminum spacer in the IGU also will reduce convective heat loss at the eog and framing. Stainless steel spacers are available that are thinner than aluminum and inherently less conductive. Aluminum is nearly 10 times more conductive than stainless steel.

5.9 COMPUTER THERMAL MODELING

Three computer programs (Optics, Window, and Therm 2006) are available for free download (windows.lbl.gov/software) that are specifically written to evaluate the optical, thermal, and solar performance of glazing and cladding. They were written by the Windows and Daylighting Group at Lawrence Berkeley National Laboratory in California. The programs are updated regularly along with a glazing database of commercially available glazing called the International Glazing Database (IGDB). The IGDB contains more than 1,000 entries from numerous suppliers. Products range from clear glazing of all thicknesses to tinted lites, reflective coated lites, low-e coated lites, laminated lites, and more. The IGDB is the source of glazing products used by Optics, Window, and Therm.

Optics is useful for comparing transmittance and reflectance among glazing products in the IGDB over the solar and long-wave spectrums. It allows easy evaluation of the spectra transmitted and reflected by the various low-e products available. Existing products also can be modified if not available in the IGDB. For example, most lites in the database are nominally 6 mm thick. If the optical properties of a 10 mm lite were needed but only 6 mm were available, a new lite can be created as a user-defined product and Optics will calculate its optical properties.

Window is used to calculate curtain wall opening u-value, VT, and SHGC based on National Fenestration Rating Council (NFRC) standard conditions. IGUs can be assembled from the IGDB in database format, and optical and thermal performance comparisons made. Framing models can be imported from Therm and assembled as a glazing assembly to determine overall opening u-value, VT, and SHGC. Window is set up to take glass and frame thermal properties from lists the user specifies and use them to perform area-weighting calculations for u-value and SHGC making it much faster to work with than a spreadsheet.

Therm is a two-dimensional heat transfer finite element program used to model eog and framing members. It imports IGUs from Window for modeling eog and can import .dxf files from drafting software to create profiles of framing members and their materials. It has its own library of standard building materials with associated thermal properties, although user-defined materials can be created if not in the library. Therm can calculate frame and eog u-values and SHG coefficients for use in assembling glazed openings in Window as well as provide temperatures for use in evaluating condensation.

5.10 FURTHER READING

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Struabe, J., and Burnett, E. (2005). Building science for building enclosures. Building Science Press, Westford, MA.

Therm 5.2/Window 5.2. (2006). *NFRC simulation manual*. University of California, Lawrence Berkeley National Laboratory, Berkeley, CA.

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CHAPTER 6

WATERPROOFING DESIGN OF CURTAIN WALLS

Gary W. Brown

Waterproofing design of curtain walls is critical to maintaining the safety, comfort, and thermal performance of a building and its occupants. Although rain, especially when driven by wind, provides the greatest challenges to the waterproofing professional, other factors, such as condensation, must be accounted for also. Gravity, kinetic energy, air pressure differentials, surface tension, and capillary action all work to provide a means for water to enter into buildings. This chapter discusses the natural forces that act on a curtain wall and some of the solutions that various systems use to maintain the watertight integrity of the building.

6.1 DESIGN TO CONTROL CONDENSATION

The curtain wall often is designed to resist surface condensation, which is described in Section 5.8 of this primer. The curtain wall must incorporate various features such as thermal breaks for the frames, double or triple glazing for the vision area, and an insulated spandrel pan area. Connections and fasteners may also include thermal breaks or thermal separators. Frame geometry for thermally conductive aluminum frame materials can be altered to minimize the proportion of framing exposed to the outdoors.

6.1.1 Thermal Breaks

Aluminum has a very high thermal conductivity. Many manufacturers incorporate thermal breaks with low conductivity materials, such as PVC, neoprene, polyurethane, or polyester-reinforced nylon to improve the thermal performance and condensation resistance of the assembly. Fig. 6-1 shows an example of a proprietary extruded high-performance polyamide thermal break reinforced with multi-directional glass fiber from Sota Glazing Inc. The polyamide between the aluminum frame sections at the perimeter of the glazing panes acts as the thermal break. The thermal break separates the interior (right side) aluminum material from the exterior (left side) aluminum material, effectively breaking the thermal conductivity from inside to outside (or vice versa). Separators that are less than ¼″ are termed "thermally improved."

The glazing units must be retained in the curtain wall in a manner robust enough to withstand wind loads, seismic loads, and thermal expansion. Consequently, metal pressure bars or pressure plates are fastened to the outside of the mullions to retain the glass. To prevent thermal conductivity, these systems frequently include protective gaskets, which function as thermal breaks. Because these gaskets are not expected to remain completely watertight for long-term service, a properly designed system will channel the water and vapor that enters the system at the gasket corners. Ideally, moisture will be managed correctly to weep out through the snap cover weep holes or other drainage slots.

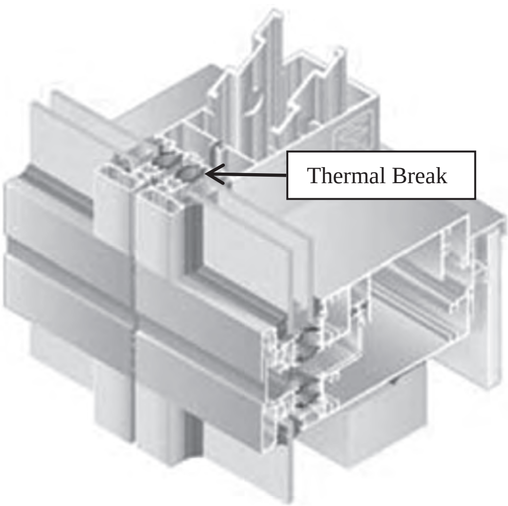

Fig. 6-1. Sota Glazing Thermo 3-series
Source: http://www.sotawall.com/products/#Thermo; reproduced with permission from Sota Glazing Inc.

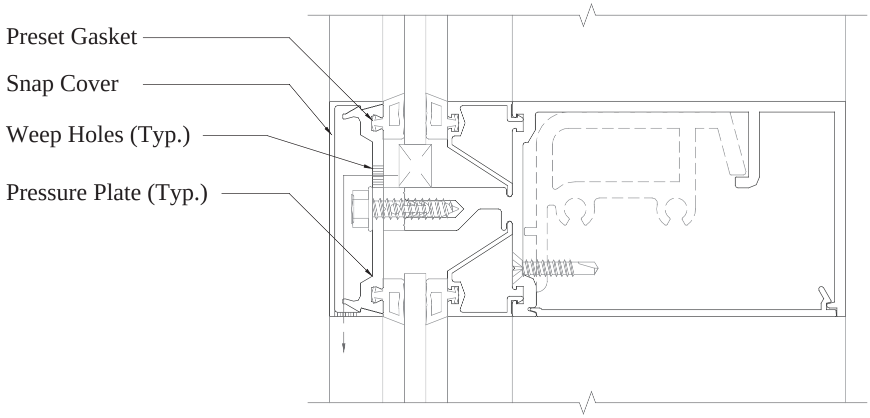

Fig. 6-2. EFCO 2-1/2″ Curtain Wall _CMA Certified System 5900T, outside glazed details: 505 O.G. HORZ
Source: http://efcocorp.com/images/products/Curtainwall/5900/2.5%20inch/Outside%20Glazed/Details%20(full%20sheets)/5925c323.pdf; reproduced with permision from EFCO, a Pella company

Figure 6-2 shows a typical pressure-glazed system by EFCO Corporation (System 5900 [T]). The glass is retained at an interior mullion with the use of an exterior pressure plate and snap cover with weeps drilled per the manufacturer's requirements. According to the manufacturer's installation instructions, the vertical gasket runs through the joint plug notch at the horizontal location, and all corners of the gaskets are sealed. Many other manufacturers use similar technology.

6.1.2 Insulation

Thermal performance of opaque areas of the curtain wall is a function of insulation and air or vapor barriers. Proper placement of insulation at the curtain wall perimeter reduces energy loss and potential condensation issues. Mineral wool insulation at the perimeter of the building provides thermal performance in addition to fire protection. The International Building Code (ICC 2012) requires that an approved system such as mineral wool be used to provide a barrier to prevent vertical fire spread in the interior void between the exterior curtain wall and the floor assembly. As seen in Fig. 6-3, Thermafiber Safing and FireSpan 90 insulation are installed in the void between the slab edge and the curtain wall to provide firestopping. These materials also minimize the potential for condensation in unconditioned space.

Fig. 6-3. Thermafiber perimeter fire barrier system with Thermafiber Safing and FireSpan 90 insulation
Source: http://www.thermafiber.com/images/uploads/pdf/safing%20data%20sheet.pdf; reproduced with permission from Thermafiber, Inc.

6.1.3 Software

Computational fluid dynamics (CFD) software can help establish a reasonable estimate for air temperatures at the inside surfaces of the glass and frame. Projects for which condensation control is a critical concern, such as high interior humidity buildings, require project-specific finite element analysis thermal modeling using software such as Therm. Therm is a state-of-the-art, Microsoft Windows–based computer program developed at Lawrence Berkeley National Laboratory (LBNL) for use by building component manufacturers, engineers, educators, students, architects, and others interested in heat transfer. Therm models two-dimensional heat-transfer effects in building components, such as windows, walls, foundations, roofs, doors, appliances, and other areas, where thermal bridges are of concern. Therm's heat-transfer analysis allows evaluations of the product's energy efficiency and local temperature patterns. These specific details may relate directly to problems with condensation, moisture damage, and structural integrity. Fig. 6-4 shows screen shots of the input/output that Therm provides to a designer. The top screen shot shows the model with various building components identified by different shades, and the bottom screen shot shows the resultant temperature gradient as calculated by the program. This particular screen shot shows that the temperature outside is cold, and it moves toward warm in a distinct pattern.

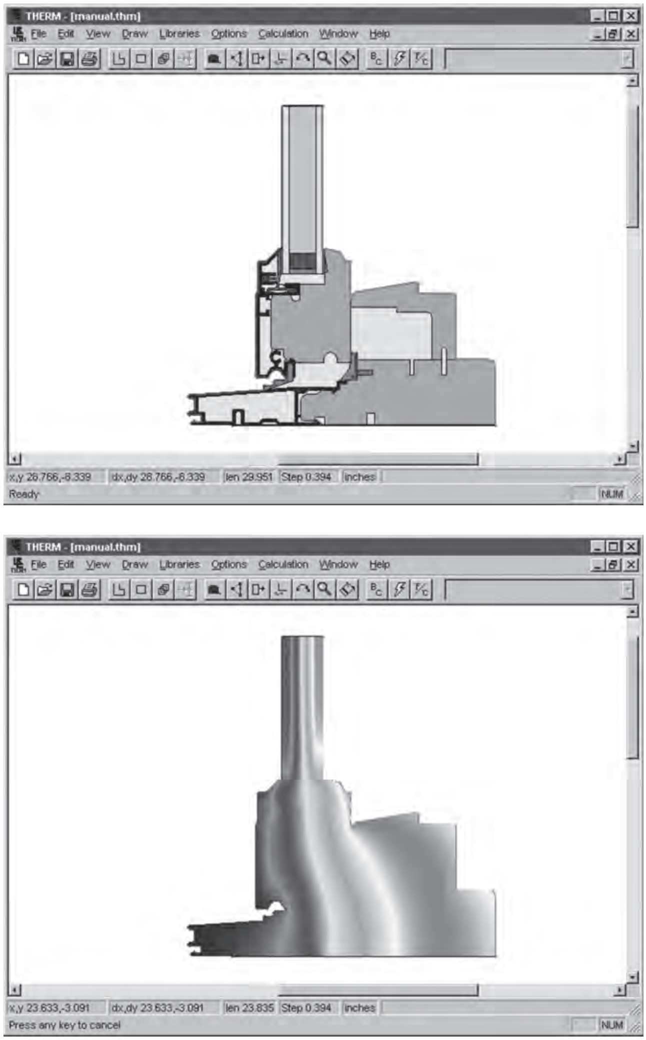

Fig. 6-4. Input/output from Therm
Source: Lawrence Berkeley National Laboratory, THERM 5.2/WINDOW 5.2 NFRC Simulation Manual

6.1.4 CRF

The American Architectural Manufacturers Association's (AAMA) *AAMA/NWWDA 101/I.S.2-97, Voluntary Specifications for Aluminum, Vinyl (PVC) and Wood Windows and Glass Doors* (AAMA 1997) provides condensation resistance guidance for windows. The larger the CRF number the greater the resistance to condensation. O'Brien (2005) states that AAMA intends designers to use the CRF in construction specifications to prescribe a level of condensation resistance for fenestration products. Both the glass area and the frame are tested at various locations to determine the interior and exterior temperatures with a thermocouple device. If a designer wants to reduce the chances of condensation occurring on the windows in a building, he or she will specify a high CRF. In warmer climates, a designer may specify a lower CRF, as the risk of condensation on windows is reduced and the cost savings associated with buying windows with lower CRFs is more attractive.

6.2 RAIN WATER FORCE AND POTENTIAL RAIN PENETRATION

Curtain walls cover large expanses of wall and often do not employ sill flashings at each glazed opening. Watertight frame corner construction and good glazing pocket drainage, where applicable, are critical to prevent water penetration to the interior or onto insulating glass below.

Vigener and Brown (2009) state that "water penetration resistance is a function of glazing details, frame construction and drainage details, weather stripping and frame gaskets, interior sealants and perimeter flashings and seals." These components counteract the five different forces that contribute in whole or in part to water intrusion: gravity, kinetic energy, air pressure difference, surface tension, and capillary action.

Wind loading, which is described in depth in Chapter 7 of this primer, creates pressure differentials caused by a variety of factors. Wind loads are calculated into pressures based on wind speed in a geographical region, building height, and other dimensional characteristics. Exposure to water in urban or suburban settings, type of building, and other factors are characteristics that are unique to that particular building. These pressure differentials can cause windblown rain to exceed the force of gravity and allow water to travel "uphill."

Thermal expansion of various building materials can affect directly or indirectly the capillary influence and surface tension characteristics of the curtain wall components. As materials expand and contract at similar or different rates in reaction to temperature changes, the joints can become tighter than anticipated, thereby enhancing capillary action between the components. For example, a 10-ft piece of aluminum framing will expand more than 1/8 in. in a 100°F temperature swing (at summer extremes vs. winter extremes), whereas glass will expand less than half this amount. Similarly, the curtain wall materials generally interact with other building materials via abutment to columns or wall panels and via wall anchorages. Surface tension characteristics of the assembly can change in response to these expansions or contractions resulting in unintended consequences. Seals, gaskets, and movable joints must be designed into the system to accommodate the differential movement among these elements.

6.2.1 Design and Detailing of Flashing and Weep Holes

Curtain wall design should start with the assumption that external glazing seals, perimeter sealant joints, and curtain wall sills are not water tight. Each type of system has its own unique method and components to shed or manage moisture. Structural silicone glazed (SSG) systems may appear to be reliant on sealant only, but in fact they rely on a complete waterproofing system as shown in the following examples. Unitized systems, which are manufactured in a plant setting and installed in large sections in the field, are self-contained and compartmentalized. Stick-built systems are "manufactured" in the field and rely on careful integration of adjacent parts and pieces to remain watertight at joints and interfaces.

Pressure-equalized systems are designed on the premise of compartmentalization and venting. Integration of perimeter flashings helps ensure watertight performance of pressure-equalized curtain wall and its connection to adjacent wall elements. The drainage system must be designed to manage condensation and rain in all cases. Drainage features include frames sloped to the exterior, large closely spaced weep or vent holes, and drainage at each horizontal mullion. Manufacturers and designers will coordinate the placement of the setting blocks with the weep holes to avoid blocking drainage paths.

6.2.2 Structural Silicone Glazed (SSG)

Two-sided and four-sided SSG curtain wall systems have stringent performance requirements for sealant adhesion and air or water infiltration at the exterior face and at the frame/glass interface. The moisture infiltration control is provided by drainage cavities in the system behind the structural silicone sealant directing water to weep holes at the stack joint.

Fig. 6-5 depicts a unitized system SSG stack joint by Kawneer. Water flows down the drainage cavity in front of the air seal and will weep at the sill in a manner such as is seen in Fig. 6-6. Fig. 6-6 depicts a SSG curtain wall system (YCW 750SSG) by YKK Corporation of America. The perimeter of the frame is sealed and weep holes are drilled into the sill of the perimeter anchors at specified intervals. The perimeter sealant is a critical component and should be coordinated between the manufacturer of the curtain wall system and the sealant manufacturer. Any substrate adhesion issues at adjoining construction must be coordinated as well. In some instances, primer may be needed to ensure a proper seal.

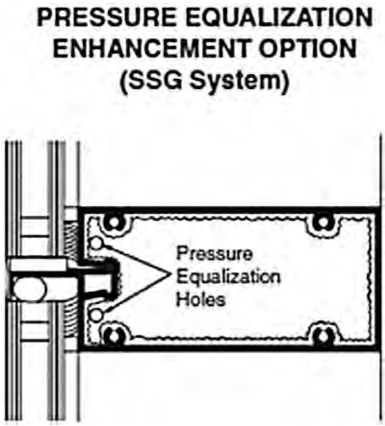

Fig. 6-5. Kawneer Series 2500 PG unit wall architectural details, 2008
Source: http://www.kawneer.com/kawneer/north_america/catalog/pdf/2500_PG_Wall–A.pdf; reproduced with permission from Kawneer, an Alcoa Company

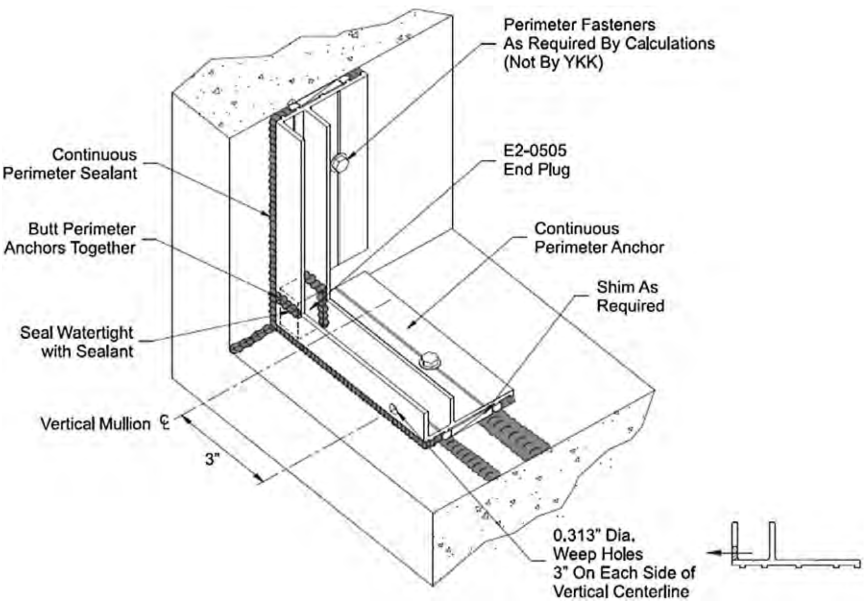

Fig. 6-6. Detail of YCU 750 TU unitized curtain wall system
Source: YCU 750 TU Unitized Curtain Wall System Installation Instructions, November 2009; reproduced with permission from YKK Corporation of America

6.2.3 Unitized Curtain Wall

Unitized curtain wall systems often are installed using the pressure-equalized rain screen (PER) concept. PER systems block the forces that can drive water across a barrier. The air pressure differential is the predominant force that drives a considerable amount of rainwater into the wall assembly according to Rousseau, Poirier, and Brown of the Canadian National Research Council. According to Rousseau et al. (1998), this principle was formalized by Birkeland (1962) and Garden (1963). In its basic form, the outer cladding (screen) blocks most but not all of the water; the pressure-equalization chamber consists of airtight self-contained compartments, and the open joints or air vents allow air pressure to vent, equalize, and eventually drain any moisture at the sills that may enter the system. The concept is common with many unitized systems manufacturers. Wet glazing and pocket sills that collect water that penetrates the glazing should be sloped to drain toward the exterior of the system.

YKK Corporation of America further compartmentalizes its unitized curtain wall (YCU 750 TU) by requiring the installation of a preformed silicone splice sleeve in a full bed of silicone sealant where the unit heads meet each other as shown in Fig. 6-7. The sill sections

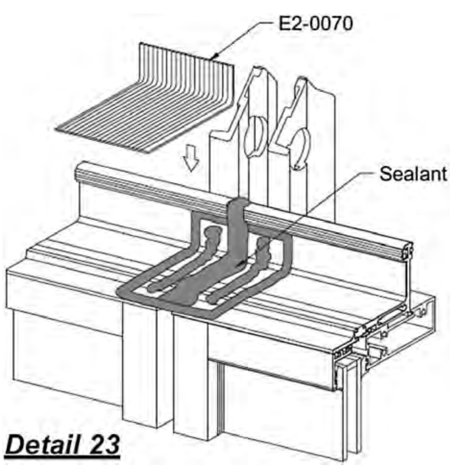

Fig. 6-7. Detail 23 of YCU 750 TU unitized curtain wall system
Source: YCU 750 TU Unitized Curtain Wall System Installation Instructions, November 2009; reproduced with permission from YKK Corporation of America

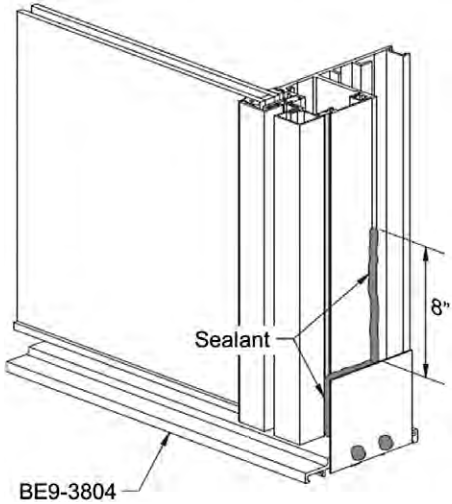

Fig. 6-8. Detail of YCU 750 TU unitized curtain wall system
Source: YCU 750 TU Unitized Curtain Wall System Installation Instructions, November 2009; reproduced with permission from YKK Corporation of America

ultimately terminate at end dams (vertical components that separate the adjacent construction) where they meet the jambs. The unitized system is sealed to the end dam to prevent migration of moisture from one component to the next. This installation is shown in the isometric view of Fig. 6-8.

In the 1602 System by Kawneer, the specifications state, "Water Drainage: Each lite of glass shall be compartmentalized using joint plugs and silicone sealant to divert water to the horizontal weep locations. Weep holes shall be located in the horizontal pressure plates and covers to divert water to the exterior of the building." Fig. 6-9 depicts the Kawneer system.

6.2.4 Stick -Built Curtain Wall

The Oldcastle BuildingEnvelope Reliance™ (1-in. glazed) (Oldcastle 2010) is a stick-built system. As stated in the installation manual, "the air and water performance of the Reliance curtain wall system is directly related to the completeness and integrity of the installation process both the seal installed at the shear blocks and the glazing gasket installed at

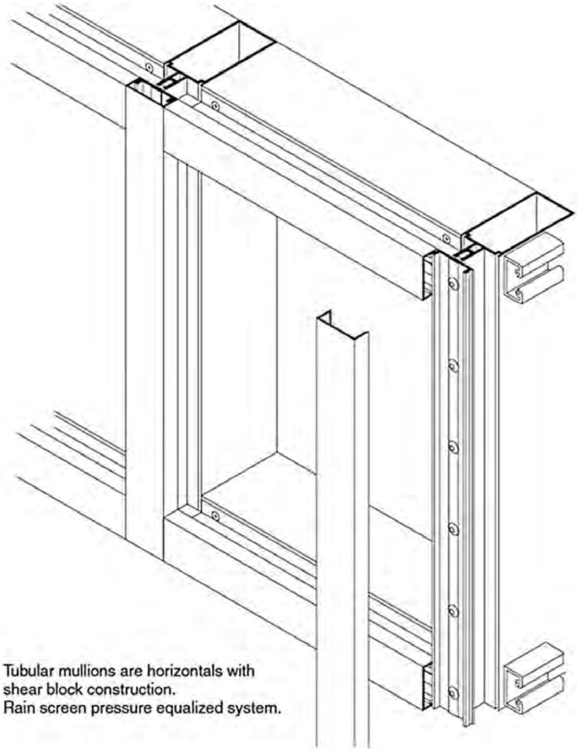

Fig. 6-9. Detail from Series 1600 curtain wall architectural details
Source: Series 1600 Curtain Wall Architectural Details, 2010; reproduced with permission from Kawneer, an Alcoa company

the interior side of the glass. All pressure plates must also be installed properly." The installation of "zone plugs" shown in Figs. 6-10 and 6-11 are designed to divert water from the verticals onto the horizontals where it is wept out of the system to the exterior at the horizontal pressure plate. These figures also show the installation of mullion end caps, which are designed to maintain continuity at the perimeter seal and extend the perimeter sealant line out at the mullion to simplify the installation.

6.3 CONCLUSION

All curtain wall systems are designed to manage water infiltration and condensation. They may vary in design or installation technique, but

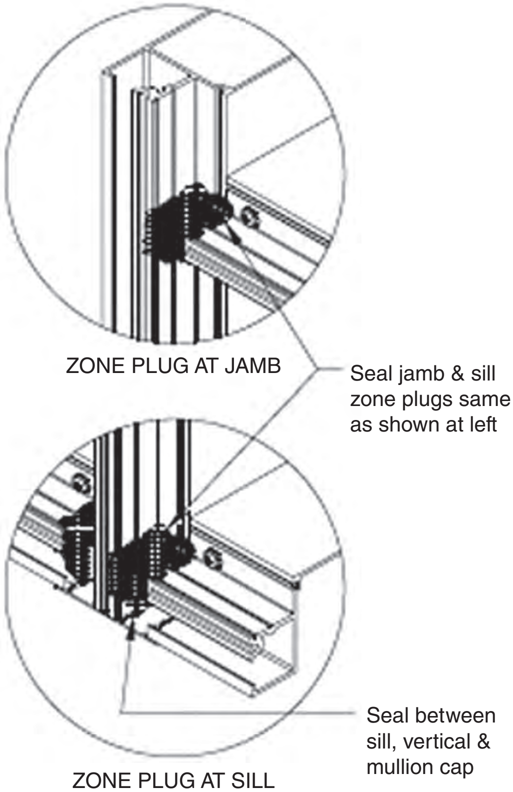

Fig. 6-10. Detail from Reliance IM 1″ installation manual
Source: Reliance IM 1″ installation manual, August 2010, http://www.oldcastlebe.com/sites/default/files/Reliance-IM_r5.pdf; reproduced with permission from Oldcastle Building Envelope, Inc.

the ultimate intent is to keep the building temperate and dry. The designer must understand the manufacturer's details and moisture strategies to make certain that unintended circumstances, such as blocking weep holes or cutting flashing short for interior finishes, is avoided at all times.

A pressure-equalized rain screen system will simplify the designer's job by allowing nature to do much of the work to combat the forces to which the curtain wall will be subjected. The air seals, air barriers, and venting must be carefully inspected, but the long-term performance of the system will be well worth the initial attention to detail.

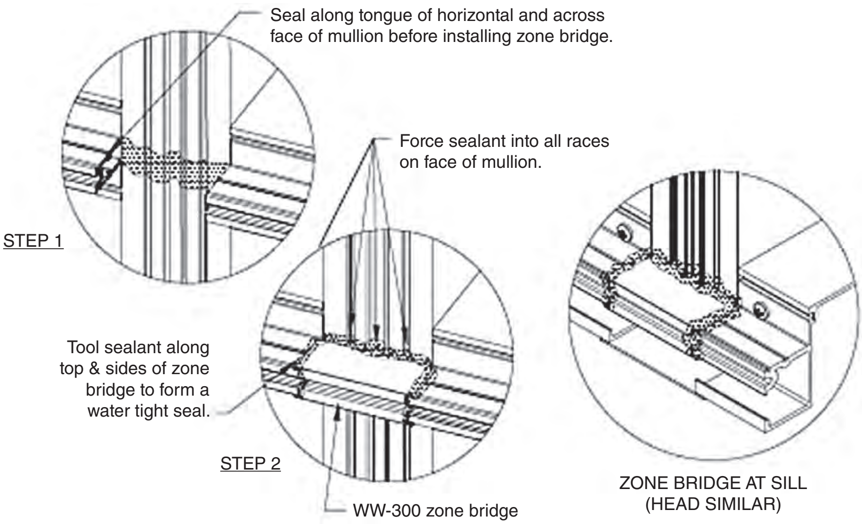

Fig. 6-11. Detail from Reliance IM 1″ installation manual
Source: Reliance IM 1″ installation manual, August 2010, http://www.oldcastlebe.com/sites/default/files/Reliance-IM_r5.pdf; reproduced with permission from Oldcastle Building Envelope, Inc.

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CHAPTER 7

DESIGN OF CURTAIN WALLS FOR WIND LOAD

Charles D. Clift and Noah Bonnheim

A curtain wall is usually the first building component loaded by wind. The curtain wall engineer intuitively knows that wind effects on a structure will probably control the system's structural design, but the process of quantifying appropriate design criteria is not obvious. This process involves bluff body aerodynamic analysis, rigorous consultation with and adherence to established code sources, careful selection of material composition and geometry, consideration of manufacturing and installation limitations, and other considerations. The process requires accurately tracing a wind load from its initial interaction with the outer curtain wall panel surface to its perimeter supports, onto its framing members, and finally to the building's primary structure. Attention to detail is paramount. The curtain wall industry requires material quantity optimization on a scale far greater than the structural steel or concrete industries. Most structural engineers trained in steel and concrete construction round off to the nearest inch, but the expense of aluminum alloy materials and the intricate fit of detail assemblies in the curtain wall industry require accuracies to more than one thousandth of an inch.

Successful curtain wall design for wind loads requires the ability to model three-dimensional objects as they are acted on by a load and forecast how that load is distributed and resisted in a structure. Modeling techniques include free body diagrams and finite element analysis using computer software, among others. This analysis requires a conceptual understanding of the design components and hierarchical structure of curtain walls.

7.1 DESIGN OF CURTAIN WALL COMPONENTS

The dominant structural features of a building that affect curtain wall design are the stacks of floor slabs arrayed as horizontal elements that circumscribe the building's perimeter. These continuous and usually stout structural elements provide ideal locations for anchorage of a wall system. Hence the curtain wall is organized as vertical elements hanging over the side of each perimeter and spanning continuously from floor to floor. The curtain wall framing system, its connection assemblies, and its anchorage to the primary building structure are where the curtain wall engineer really focuses effort.

7.1.1 Hierarchy for Structural Design and the Load Path

The first element loaded in a curtain wall is a large area of glazing or other panel surfaces that bluntly resists oncoming wind pressure. These panels then transfer their load to stiffeners or perimeter supports. The perimeter supports either directly or indirectly dump load to linear continuous framing members. These framing members often are arranged in an orthogonal grid pattern of beam-column mullions that span from floor to floor and transfer accumulated loads to the primary building structure. These last supports are designed as embedded anchors with direct welding or bolting to steel and concrete components (Fig. 7-1).

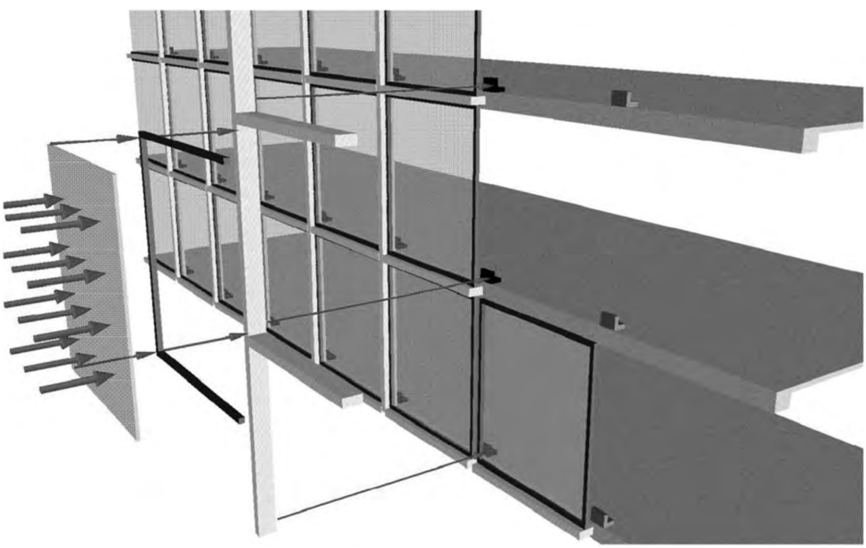

Fig. 7-1. Basic curtain wall structure; wind load flows from the panel surface to perimeter supports, onto framing members (vertical mullions and horizontal beams), and finally onto the building's primary structure

Horizontal framing members will in-fill between vertical mullions to act as secondary elements carrying portions of wind and dead loads to the primary wall elements. Generally, a rectangular panel or glass unit is assumed to be continuously supported around its edges by these horizontals and verticals. The priority of using vertical mullions as the primary framing members is valid in stick-built or unitized designs.

The curtain wall engineer needs to communicate the final reaction values and locations exerted by the curtain wall on the primary building structure to the building's structural engineer. This coordination will confirm the building's capacity to receive and resist curtain wall loads properly.

If wall openings are present during a wind event, alternate load paths may occur. Interior pressures can develop that may or may not act in concert with exterior pressures. This scenario should be considered in projects that have, for example, operable windows and doors, vestibules, and large mechanical ventilation areas.

7.1.2 Design of Glass Thickness

Architectural flat glass is a proprietary product that enjoys a very high profile, often as the most significant visual feature of a building. Current structural analysis of glass has been somewhat codified using the American Society for Testing and Materials (ASTM) E1300 (ASTM 2009a). Sizing of glass thickness will involve engineering parameters and issues related to aesthetics and manufacturing.

To size glass thickness properly, the basic influences are values of span and load. Shading temperature effects also may affect design for stress capacity. Heat treatment of flat glass during the manufacturing process has a significant effect on strength by prestressing its surface. Industry standard requirements have been established that define stress limits for three glass types: annealed, heat strengthened, and fully tempered. The controlling influence with respect to load is usually wind pressure; however, some projects require blast loading or debris impact conditions. Typically, the glass manufacturer will provide review and analysis of applications on a specific project and render its approval. Architects will write performance specifications that may have deflection limits or other items that influence design of glass lites. The Glass Association of North American (GANA) publishes a glazing manual that contains in-depth presentation of technical considerations for glass design (GANA 2008).

Stiffness design of glass panels is somewhat subjective. Limiting the magnitude of center of glass deflection should include considerations of occupant comfort, interference with adjacent materials, potential for accumulated movement, or loss of bite. Distortion from heat treatment of glass may be minimized by selection of thicker panels to improve flatness.

Boundary conditions for structural modeling of glass panels typically are assumed to be continuous simply supported edges for common perimeter details such as dry gasket pocket glazing or structural silicone glazing (see 7.1.3). Lateral pressures are assumed to be uniformly distributed over the entire surface area of the glass panel. Load duration and tributary area effects are taken from the American Society of Civil Engineers and the Structural Engineering Institute publication called Standard 7-10 (ASCE 2010).

7.1.3 Structural Silicone Glazing

Structural silicone glazing (SSG) is a technique that adheres lites of glass to perimeter framing (Fig. 7-2). In lieu of a traditional glazing pocket design, SSG can accomplish a flush profile of glass-to-glass surfaces without any exposed metal. When all four edges of a typical glass lite are adhered with structural silicone, the only component holding the unit against wind load is the rubber adhesive. Because no mechanical restraints sit around the edges of the glass, structural engineering experience must merge with hyper-elastic rubber theory to achieve integrity.

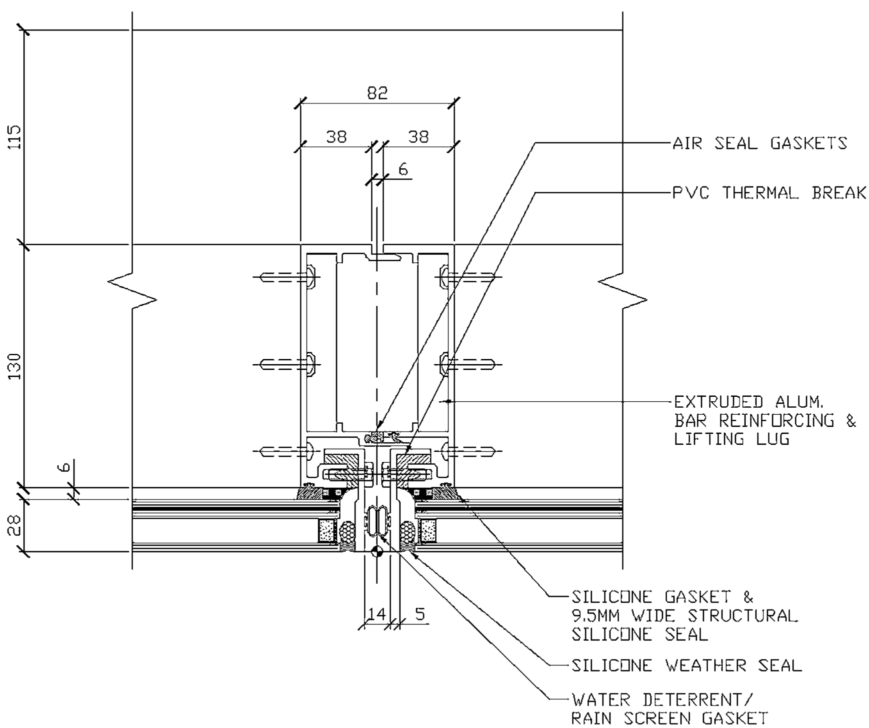

Fig. 7-2. Plan view of a structural silicone glazing design

Besides out-of-plane wind loading, one of the other possible options with SSG is to design the glass panel as a diaphragm to resist in-plane forces. The small but continuous bead of structural sealant offers considerable shear and tension values that directly transfer in-plane edge shear forces. This characteristic of SSG is particularly helpful in designing corner conditions in curtain walls. To control loss of glass bite due to in-plane force vectors at corners, one may estimate resistance by dividing the load over the perimeter length of SSG and comparing to allowable strength.

The critical issue with SSG is accomplishing a secure bond between substrates of glass and aluminum. The wide selection of glass coatings and metal finishes available makes sealant compatibility testing a challenge. Proprietary silicone products have been developed by a few manufacturers. These materials have been rigorously tested and now have a substantial history of successful performance.

7.1.4 Point-Supported Glass

Pilkington's Planar Wall System (http://www.pilkington.com/resources/planar.pdf) and PPG's old Total Vision System walls are usually the starting point for examination of point-supported glass designs. Early designers used "patch" fittings, which are small rectangular metal clamps at discrete points around the glass perimeter in lieu of continuous glazing channels or pockets. Eventually, these patches were supplanted by drilling holes completely through the glass thickness and installing tee-headed bolts or button discs to restrain the panel. Today, some manufacturers use countersunk holes in the glass so that no metal fixture is visible on the outside surface, just the bolt hole itself (Fig. 7-3). Dimensions required for countersunk profile will influence selection of glass thickness.

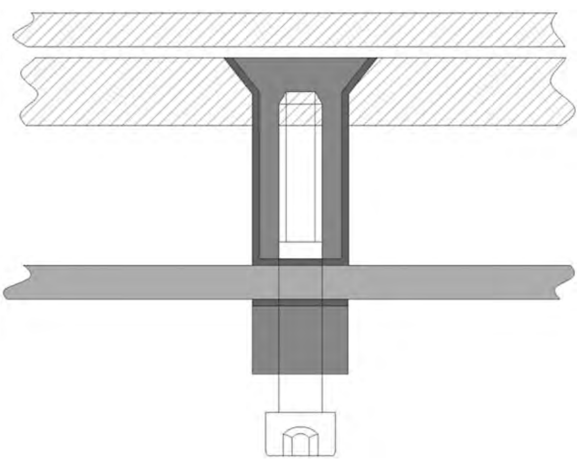

Fig. 7-3. Plan view of a countersunk hole design

There is no requirement for continuous framing support along each glass panel edge, thus many types of structural systems can be used to collect the point-support locations. In lieu of an orthogonal grid of aluminum framing, designers use spider fittings on space frames, tension structures, and cable networks to emphasize the creative freedom of support styles. However, ASTM E1300 does not address point-supported glass boundary conditions, so finite element analyses via computer programs with large deflection capabilities are needed (e.g., ANSYS; see 7.3.3). Fracture mechanics will control failure behavior, so while advanced finite element analyses are possible, concentrated stress around the hole at a point support may require empirical data to verify capacity.

7.1.5 Structural Glass

Structural glass is a largely uncodified area of building design and construction. Vertical glass fins, which perform like vertical mullions in a curtain wall, are the most recognized type of structural glass design (Fig. 7-4). However, structural glass doors, like PPG's Herculite doors, are the most common use of glass as a structural material. The wildly popular Apple store designs (http://www.apple.com/retail/fifthavenue/), using all glass structure to frame and enclose the building as well as all glass stair designs, have really pushed the envelope for glass as a primary

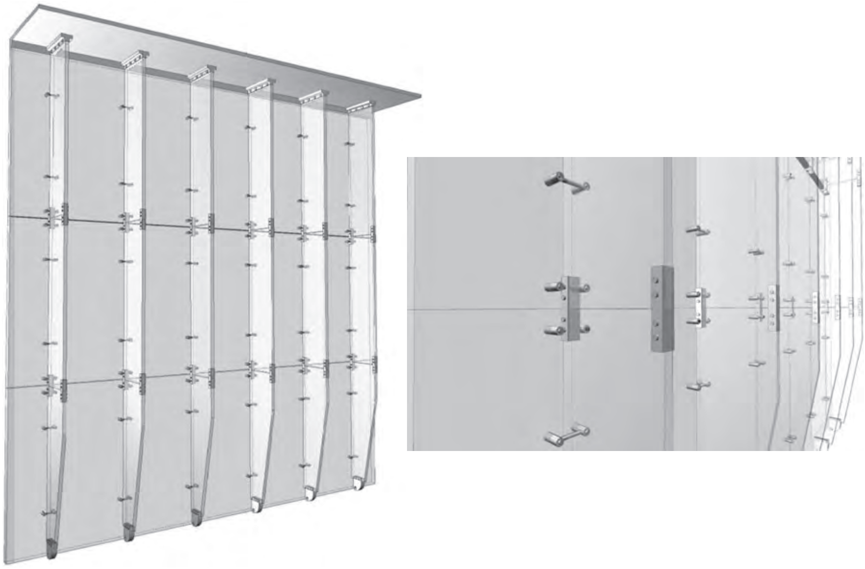

Fig. 7-4. Structural glass mullions combined with point-supported glass

structural building material. Because glass breaks, often suddenly and catastrophically, rigorous evaluation must be made to provide structural integrity. Redundant load paths, sacrificial plies, large safety factors, and prototypical testing are necessary to provide a reasonable measure of stability under extreme load conditions.

Attention to detail is paramount. For example, analysis of point-bearing stress on a cylindrical surface is not frequently a strength of building structural engineers. If the design is a steel bolt in a steel hole, the steel material's famous ductility allows simplifying assumptions that make design of steel joints fairly straightforward. Not so with a steel bolt situated in a glass hole.

Sometimes, avoiding the point-bearing stress problem is possible by using high-strength friction bolts to clamp components together. Moment splices to accomplish long glass fins employ this technique to transfer large flexural stress and avoid bearing stresses in bolt holes.

7.1.6 Importance of Scale

Most structural engineers are trained in steel and concrete construction, where dimensional measurement magnitudes often are rounded off to the nearest inch. The curtain wall industry is competitive on a global basis, and contractors are quite keen to minimize/optimize quantities of expensive aluminum alloy material. Consequently, section properties for aluminum extrusions are sized to one over one thousandth of an inch. Of course, the intricate fit of detail assemblies requires extrusion accuracies to one thousandth of an inch.

The magnitude of deflections is also a critical issue for curtain wall design. For example, nominal glass bite of one-half inch (½″) may be reduced by one-eighth inch (⅛″) due to fabrication tolerance or setting tolerance of the glass panel. Hence structural movement that might decrease the bite by an additional one-eighth inch (⅛″) would result in a 50% reduction of the nominal bite. Live load deflection at perimeter spandrel beams has a particularly significant effect on design of wall expansion joints. Deflection values greater than one-quarter inch (¼″) require larger than typical site lines for wall framing and large joint profiles.

7.1.7 Manufacturing and Installation Considerations

Manufacturers expect optimization of expensive alloy material, and installers expect efficient design that simplifies work in the field. Hence, experience with fabrication techniques and equipment capabilities is necessary to make informed design decisions. Also, understanding erection rigging, construction tolerances, and skill level of the glaziers will direct choices for system design details. The curtain wall engineer's tendency will be to arrange his or her design for maximum efficiency to resist wind load. However, the competing desires of the manufacturer and the installer will need to be accommodated in a successful wall design.

Fabrication of various glass products will be limited by the capacity of equipment to process the application. In the production of raw float glass, dimensions of width or length will be limited by plant size and handling. Heat treatment will be limited by size of ovens. Laminating will be limited by size of the autoclave. Insulating assemblies may have dimensional restraints. Coating process also will have limitations.

7.2 WIND LOADS AND THE BUILDING CODE

Application of aerodynamics to building structures deals with relatively low-speed, incompressible flow phenomena and is associated with meteorology and atmospheric boundary layer turbulence. Most locations in the United States have adopted ASCE 7-10 (ASCE 2010) as the standard for design loads on buildings. Chapters 26 through 31 of that publication contain a well-developed body of information on wind loads that is geared toward use by the structural engineering designer (ASCE 2010). However, some large cities maintain their own parochial wind criteria that, while not rigorously developed like ASCE 7-10, will nonetheless control the curtain wall design.

Countries outside the United States generally have less robust wind criteria requirements. Some locales will impose artificially high wind loads to cover a lack of appropriate scientific data. Australia has an excellent wind code. In fact, the Australian code provides better information with regard to particular curtain wall design situations such as simultaneous wind pressure at building corner conditions.

7.2.1 Choice of Methods to Establish Design Loads

The choice of methods to establish design loads contained in ASCE 7-10 is divided into two sections. The first section discusses procedures for establishing wind loads for main wind-force resisting systems (MWFRS), and the second section discusses procedures for establishing wind loads on components and cladding. Wind loads for MWFRS are determined using one of four procedures: (1) directional procedure (for buildings of any height); (2) envelope procedure (for buildings with a mean roof height of 60 feet or less); (3) directional procedure for building appurtenances and other structures (for rooftop structures and equipment, such as chimneys); and (4) wind tunnel procedure (involving laboratory testing and accurate modeling of the natural atmospheric boundary layer, surrounding structures, and topography, used for buildings of any height).

Wind loads for components and cladding are determined using one of two procedures: (1) analytical procedure (involving highly detailed charts and formulae to determine design wind pressures for building of any height) and (2) wind tunnel procedure. Typical curtain wall designs usually follow the analytical procedure; however, large or unusual projects may employ a wind tunnel procedure. Because the analytical method of analyzing components and cladding can become so involved, ASCE offers periodic seminars to instruct engineers on appropriate usage.

7.2.2 Load Combinations

Structural design of curtain walls has largely continued to be done by the allowable stress method. The Aluminum Association's *Aluminum Design Manual* (AA 2005) contains specifications for both the allowable stress method and building load and resistance factor design method (2005). Other industry standards, such as the American Architectural Manufacturers Association's TIR-A9-91 (AAMA 1991), establishes fastener design in an allowable stress format.

Load combinations are provided in ASCE 7-10. Though the text includes some wind load combinations, it is directed toward the primary building structure more than exterior cladding, and the discussed load combinations are therefore more relevant to vertical loads than horizontal wind loads. For the curtain wall engineer, the "live load" variable presented in the ASCE 7-10 is treated as the wind load. For example, the equation (1.0 × dead load) + (1.0 × live load) presented in the ASCE 7-10 becomes (1.0 × dead load) + (1.0 × wind load). This load combination often is used because it usually produces the most critical effect on the building.

For some anchor designs, negative wind load (outward acting pressure) will counteract moment from a dead load eccentricity. The load combination presented in ASCE 7-10 is (0.6 × dead load) − (0.6 × wind load). However, because the ASCE 7-10 is more concerned with vertical loads than wind loads (unlike the curtain wall engineer), this equation should be rewritten (0.6 × dead load) − (1.0 × wind load) so as not to underestimate the effects of wind on curtain wall structure.

The use of an increase in allowable stress is not allowed on loads or on load combinations defined in ASCE 7-10 unless the increase can be justified by material behavior caused by duration of load or by the rate of load application. The engineer will need to be familiar with other code requirements and product manufacturer's data to ensure consistent application of safety factors.

The combinations of different types of stress (axial, bending, and shear) that interact simultaneously are addressed in the Aluminum Association's *Aluminum Design Manual*. The engineer will need to organize analysis results with respect to orientation of principle stresses and account for any unsymmetrical bending conditions.

Load combination philosophy also seems to intersect with serviceability issues, in particular with deflection limits on curtain walls. The industry standard has long been established by the AAMA Specifications Guide and presented in AAMA TIR-A11-04 (AAMA 2004). A somewhat radical deflection limit is contained in the 2009 International Building Code (IBC; International Code Council 2009).

7.2.3 Safety Glazing

Requirements for safety glazing are contained in the building codes. Glass adjacent to pedestrian walking surfaces, glass in doors and operable windows, overhead glazing, and glass in fire-rated assemblies are some of the conditions that should be investigated with respect to safety glazing. Often, glass designed for safety glazing purposes will exceed requirements for glass design under wind load.

7.2.4 Execution of ASTM E1300

ASTM E1300 contains direct instruction for the sizing of glass once geometry and load values are known (ASTM 2009a). Numerous graphs are provided for various glass thicknesses, assemblies, and support conditions. Software is available that allows organization of analyses to be accomplished efficiently for a large number of cases to be reviewed. In the United States today, the most common thickness used in glazing assemblies on high-performance commercial projects is one-quarter inch (¼″) thick glass. One inch (1″) thick insulating glass units (IGUs) are commonly made up of a one-quarter inch (¼″) outer lite of glass plus a one-half inch (½″) air space plus a one-quarter inch (¼″) inner lite of glass (Fig. 7-5).

7.2.5 Other Wind Considerations

Special wind considerations require attention, and the curtain wall engineer must be proactive in recognizing such situations. Wind-borne debris regions and any requirement for impact-resistant glazing and testing per ASTM E1886 and ASTM E1996 should be evaluated early on in project design (ASTM 2005, 2009b). When aerodynamic forces and structural motions interact significantly, the curtain wall engineer should investigate aeroelastic phenomena. Instabilities due to resonance, flutter, vortex shedding, etc., require advanced analysis techniques in the purview of a specialist wind engineer.

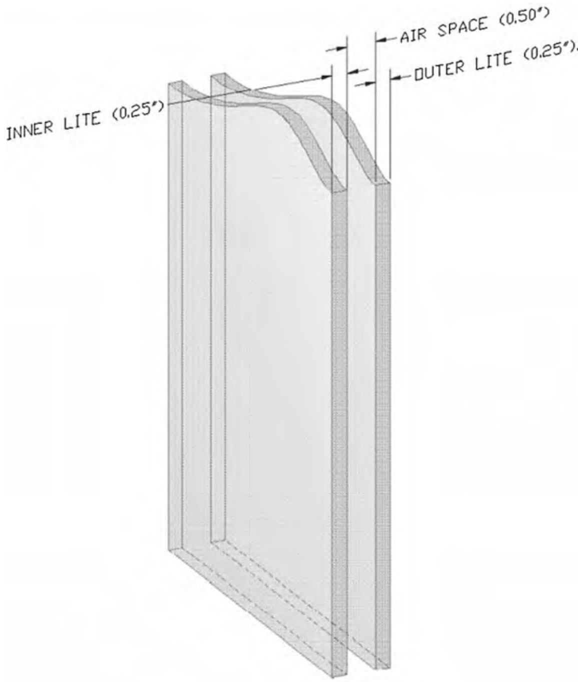

Fig. 7-5. Typical insulated glass unit (IGU) with a one-quarter inch (¼″) inch inner lite, a one-half inch (½″) middle air space, and a one-quarter inch (¼″) outer lite

7.2.6 Specifications and Code Compliance

Performance type specifications should identify governing building codes and standards for a project. Curtain wall design criteria may or may not be well presented in the architectural documents. The curtain wall engineer should compile a list of codes, standards, and other references to guide his or her design and analysis work. A detailed presentation of pertinent wall design criteria should be compiled to describe the assumptions and basis for engineering design used for the project. AAMA (1976) is the industry standard used to develop typical curtain wall specifications.

The curtain wall engineer should be diligent in making sure all code-required minimum criteria are incorporated in the design, even if the project specifications are lax. Conversely, some specifications will require stricter design criteria such as increased stiffness ratios. The engineer is responsible for highlighting such items to the project team.

7.3 WIND LOAD ANALYSIS: MODELS THAT SIMULATE STATIC EQUILIBRIUM

The capacity to visualize three-dimensional objects as they are acted on by wind loads and forecast how that load is distributed and resisted is key to successful structural design. Expertise is needed to develop analogous models that accurately define structural behavior. Parameters of geometry and load along with mechanical properties provide the raw data needed to establish system design.

7.3.1 Conversion from Dynamic Pressure to Equivalent Static Load

The conversion of fluid forces in a dynamic situation (such as wind) to an estimated equivalent static pressure is accomplished using Bernoulli's equation.[1] Hence, a significant relationship is derived that depends directly on wind velocity to determine normal pressure. Pressure is applied perpendicularly to the glazing surface of the curtain wall. Primary framing members typically are analyzed using a local uniformly distributed lateral load. Secondary framing members are analyzed using triangular or trapezoidal load patterns.

7.3.2 Free Body Diagrams

For curtain walls, the most useful simulation of structural behavior is the "free body diagram." With reference to Fig. 7-6, primary framing members (vertical mullions typically are analyzed as continuous beams spanning from floor to floor with uniformly distributed lateral loads. If significant accuracy is needed, each mullion bay can be analyzed individually using triangular or trapezoidal load patterns. Secondary framing members (horizontal beams) typically are analyzed as simply supported beams with triangular or trapezoidal load patterns. This is usually a two-dimensional stick diagram that represents a linear framing element spanning between or across support points with various boundary conditions. Horizontal framing is usually a single simple span. Load application can be analyzed as uniformly distributed or, more accurately, as triangular or trapezoidal. End conditions usually are pinned and may or may not transfer axial loads.

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[1]Bernoulli's equation, named after mathematician Daniel Bernoulli (1700–1782), is essential to fluid dynamic theory. Though it can be written in many ways, one simplified form (valid only under certain conditions) can be written $P + \frac{1}{2}\rho V^2 + \rho g h = constant$, where P is pressure, ρ is density, V is velocity, g is gravitational acceleration, and h is elevation. See Calvert (2000).

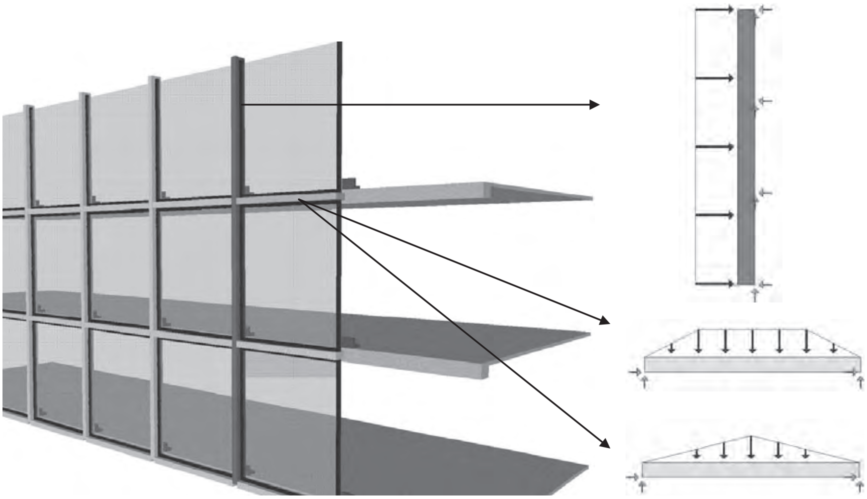

Fig. 7-6. Free body diagrams of framing members

Most attention will be given to analysis of the primary vertical framing members. Efficient design uses a continuous beam approach running from floor to floor. Limits to the length of the beams can be extrusion capacity, finish tank dimension, or transportation restrictions. Hence, locations of beam splices are necessary on multistory projects. Although the structural engineer will want to locate splices at points of zero moment, issues of aesthetics, waterproofing, and access during installation also will influence the splice location.

Frequently, deflection limits will control design of aluminum framing members. Hence, the beam splice location will need to be examined with this in mind rather than prioritize flexural stress concerns. Note that ASCE/SEI 7-10 allows variation of wind pressure magnitude as a function of tributary area (ASCE 2010). A short horizontal member may have higher wind pressure compared to a long vertical member that collects load from a large area.

7.3.3 Finite Element Analysis

Three-dimensional analyses are useful to evaluate space frame systems accurately or for panel elements (e.g., point-supported glass). Rigorous computer software (e.g., ANSYS) is available to simulate most curtain wall conditions (Fig. 7-7). Care must be exercised to use proper physical constants for materials of aluminum or glass. One challenge is to correctly model boundary conditions, because perimeters often include gaskets and flexible supports.

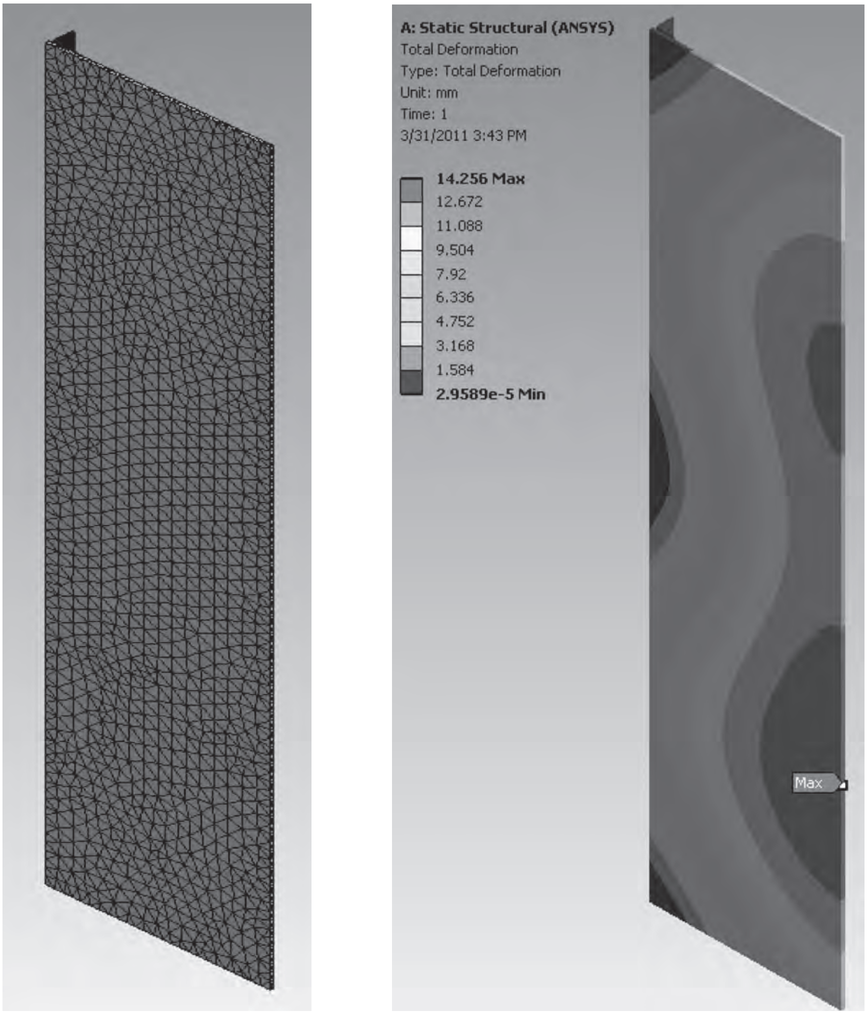

Fig. 7-7. Finite element analysis of a glass panel using ANSYS software

7.3.4 Connection Assemblies

This is the most difficult aspect of curtain wall design. Some assemblies are held together by snap fits (Figs. 7-8 and 7-9). Eccentricities are not always obvious. Boundary conditions are usually subjective. Nonetheless, the engineer must develop a model, or series of models, to simulate load transfer from, for example, horizontal member to vertical member.

Mechanical connections using fasteners or welds typically are modeled as rigid bodies with geometry of load eccentricities determining

Fig. 7-8. A pressure plate connects a panel surface to a horizontal beam; a shear plate connects a horizontal beam to a vertical mullion

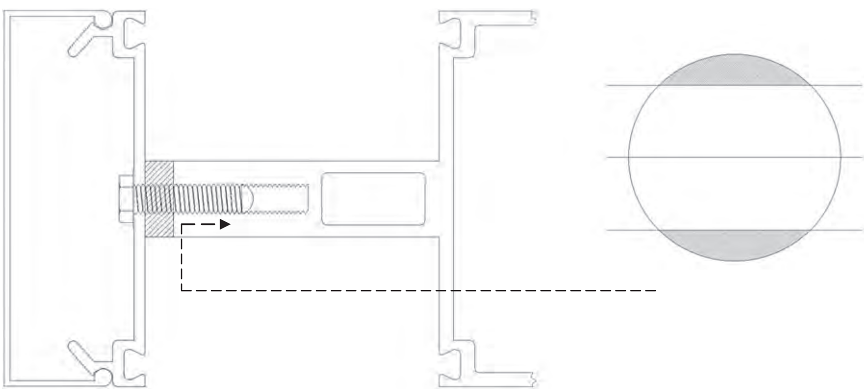

Fig. 7-9. Left: Plan view of a pressure plate connection assembly; right: Cross-section of screw in chase, illustrating thread engagement

overturning and torsion actions. Resulting tension and shear loads are compared with capacities given in AAMA TIR-A9 (AAMA 1991) or in the Specifications for Aluminum Structures by the Aluminum Association (AA 2005). Note that welding aluminum extrusions will reduce allowable strength values significantly.

7.3.5 Anchor Designs and Embeds

In addition to conventional welded steel and bolted anchors, the curtain wall engineer must be familiar with various proprietary anchor products.

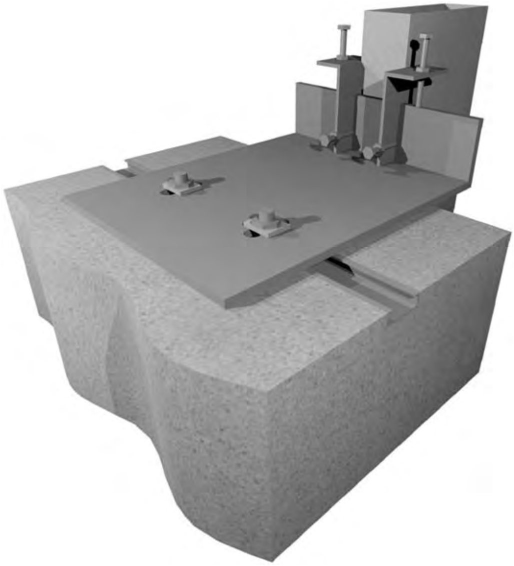

Fig. 7-10. The cast-in anchor attaches vertical mullions to structural floor elements

Slotted channels that are cast in place in concrete slabs are frequently used on high-performance wall systems (Fig. 7-10). A wide variety of postinstalled concrete anchors are often selected to provide flexibility for tolerances or for missing embeds.

The curtain wall engineer needs to coordinate anchor design assumptions with the building structural engineer. Communication must define reactions of load and moment from the curtain wall anchors onto the structure. Building structure movements, such as live load deflection and long-term creep, will also need to be accommodated at the wall-anchor interface.

7.4 PHILOSOPHY OF STRUCTURAL DESIGN FOR ALUMINUM STRUCTURES

The structural engineer typically creates a design using analogies and extrapolates or interpolates from known applications to a new situation. The design professional must accumulate an array of data and reduce the information to a critical set of variables and then consider industry knowledge with practical experience to create a new solution.

The material of choice for most curtain wall systems is a strong aluminum alloy. Attributes of the material that make this a desirable choice are its lightweight and high strength-to-weight ratio; corrosion resistance; ease of fabrication; and physical properties such as its nontoxic, nonmagnetic, electrical conductive, ductile, and heat-treatable character. The aluminum extrusion fabrication process allows geometrical configurations that provide maximum structural efficiency with lightest weight cross section and simultaneously combines multiple functions of the framing element to achieve economy of material and number of pieces required.

The computational method used in developing a curtain wall design can be separated into deterministic methods and probabilistic methods. Deterministic methods are allowable stresses in which maximum loads are compared with material strength reduced by given safety factors. This method currently dominates aluminum curtain wall design practice in the United States. The use of "service limit states" is appropriate for primary functions of cladding, which are dominated by design displacement and corrosion and not for overturning or collapse of a gravity load-bearing system. Also, hesitancy to use an ultimate limit state method may be rooted in a lack of familiarity with mechanical properties of aluminum, such as nonelastic and nonlinear effects, that become significant at the threshold of ultimate behavior. Furthermore, because curtain wall designs often employ a combination of different metal materials, organizing documentation of analytical data is perhaps simpler and more consistent using an allowable stress approach. Code wind load values and most manufacturers' product data for structural capacities are defined in terms of service limit states.

7.5 CONCLUSION

The curtain wall engineer must draw on sources outside traditional structural industries of steel and concrete. Experience and a knack for innovation are necessary to design multifunctional wall components successfully. Rigorous knowledge of wind load criteria is critical. The ability to conceptualize the load path and develop accurate structural models is key to engineering curtain wall systems.

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CHAPTER 8

DESIGN OF CURTAIN WALLS FOR EARTHQUAKE-INDUCED LOADS AND DRIFTS

Ali M. Memari

The vulnerability of glazing systems to glass damage in earthquakes is well known (EERI 1990, 1995a, 1995b, 2001). In fact, glass damage can occur in buildings that may experience little or no damage to the structural components (FEMA 1994). In general, earthquake-induced glass damage in metropolitan areas is expected to occur on a much wider scale compared with the smaller areas that would experience structural damage. Such glass damage not only poses safety hazards but also economic loss in terms of business downtime, building occupant disruption, and repair costs.

To minimize glass damage due to earthquake effects, International Building Code (ICC 2009), which adopts ASCE 7-05 (ASCE 2006), requires glazing system seismic provisions be satisfied. Note that ASCE 7-10 (ASCE 2010) has since become available at the time of this writing, and the glazing seismic provisions are the same as those in ASCE 7-05. Therefore, ASCE 7-10 is referred to in this chapter when necessary. Such provisions in general require the glazing system to accommodate the seismic-induced relative story displacement (i.e., story drift) requirements.

Glass curtain wall systems can be designed using a variety of glass types (annealed, heat strengthened, or fully tempered); configurations (monolithic, laminated, or insulating glass unit); glazing frame construction type (stick-built or unitized); and method of glass-to-frame attachment (dry-glazed or structural sealant glazing). The response of different designs is generally different under earthquake-induced building story drifts. With widespread use of various types of glass curtain wall systems, a growing need exists for better understanding of the behavior of such systems under earthquake effects and how to design them for safety and serviceability concerns.

The main objective of this chapter is to provide some basic understanding of the seismic response of different glazing systems and to discuss seismic design provisions and testing requirements. Although documents related to research and advancements in the areas of seismic testing, analysis, design, damage mitigation, and retrofit are not specifically discussed in this chapter, relevant references are suggested where appropriate for further information. A summary and review of these topics may be found in Memari and Schwartz (2009). This chapter reviews some of the lessons learned from seismic response of glass in windows, storefronts, and curtain walls in actual earthquakes. Important parameters that affect the performance of glazing systems in earthquakes are reviewed. In particular, the seismic code provisions are discussed in detail along with the mockup testing requirements to determine drift capacity corresponding to glass failure in the form of glass fallout.

8.1 PERFORMANCE OF GLAZING SYSTEMS IN PAST EARTHQUAKES

Reconnaissance reports following damaging earthquakes such as 1989 Loma Prieta (EERI 1990), 1994 Northridge (EERI 1995a), and Nisqually (EERI 2001) describe damage to structural and nonstructural components in buildings among damage to other building components and other infrastructure systems. The reconnaissance reports indicate glazing damage that included glass fracture, excessive and permanent deformation of glazing frames, and loss of attachment in adhered glass systems.

Figs. 8-1 to 8-3 show photographs of example damage to glass in past earthquakes. Glass damage has been observed both in strong earthquakes and moderate events and in varying levels and types. One observation based on past earthquakes (Evans et al. 1988) is that flexible buildings with structural damage have experienced three to four times more glass damage compared to rigid buildings with structural damage. Another observation from past earthquakes (Sakamoto et al. 1984) is that larger glass panes are more vulnerable than smaller ones.

Other important observations based on past earthquakes (EERI 1995a) include (1) more damage to low-rise storefront windows compared to glass curtain wall damage on high-rise buildings, (2) potential for cumulative glass damage because of aftershocks, (3) entire unit fallout of film-coated glass when the film is unanchored, and (4) better performance of structural sealant glazing (SSG) glass curtain walls compared with dry-glazed systems.

Fig. 8-1. Glass breakage in punched window system during Loma Prieta (magnitude 6.9) earthquake of October 17, 1989
Source: Oaklandlibrary.org/oaklandhistory/earthquake89; courtesy of John Hendry, City of Oakland DIT Department; reproduced with permission

Fig. 8-2. Damage to storefront during Northridge (magnitude 6.7) earthquake of January 17, 1994
Source: FEMA News Photo, FEMA, Washington, D.C.

Fig. 8-3. Glass breakage in strip window system during Fukuoka (Japan) (magnitude 7.0) earthquake of March 20, 2005
Source: http://en.wikipedia.org/wiki/File:Fukuoka_Earthquake_20050320_Maruzen.jpg

8.2 PARAMETERS IMPORTANT IN SEISMIC PERFORMANCE OF GLAZING SYSTEMS

The performance of glazing systems in earthquakes (FGMAJ 1995, Gates and McGavin 1998, Lingnell 1994) depends on several parameters. Glazing systems can be divided into categories of punched windows, strip windows, storefronts, and curtain walls. Because the construction of each of these glazing systems depends on how it is attached to the building, the earthquake response will be a function of the interaction between the glazing frame and its attachment to the supporting building wall or structural frame. For example, in the wall with punched windows shown in Fig. 8-4, the response of the window depends on the deformation of the surrounding wall panel. In general, if the opening in walls constructed of precast cladding panel or brick veneer, etc., with small in-plane deformation has sufficient clearance between the window frame and its surrounding, then one would expect lower probability of glass damage. However, if the window frame-to-wall clearance is small or the caulking material between the window frame and the wall is not deformable, then the probability of glass damage will depend more on the glass-to-window frame clearance and the type of glass used.

Unlike punched windows that are surrounded by the wall or cladding on all four sides, strip windows as shown in Fig. 8-5 are more likely

Fig. 8-4. Example of a punched window in a multistory building

Fig. 8-5. Example of a strip window in a multistory building

surrounded by spandrel panels at top and bottom, and in some cases, the end segments of the strip window also may be surrounded by vertical cladding panels. In general, strip windows experience story drift proportional to their heights as the top spandrel tends to move horizontally with respect to the bottom spandrel. In such cases, the behavior of the glazing system will depend largely on the method of attachment of the window frame at top and bottom to the cladding panel or spandrel panel. For example, if the strip window frame to spandrel connection at top of the window employs any isolation joint that allows sliding of the horizontal mullion (transom) with respect to the spandrel, then the damage is expected to be lower than a more rigid connection.

Storefronts are constructed in different ways, in many cases not necessarily planar, as in Fig. 8-6, which shows a typical storefront in a shopping mall. Because of the use of nonplanar panel geometry in storefront systems (e.g., re-entrant or interior corners), such systems have sustained relatively more damage compared with other types of glazing systems. However, modern and code-conforming designs of storefronts have shown to have large drift capacities with less likelihood of extensive damage (Memari et al. 2011a). In general, storefronts are supported on or near the first floor and span vertically to the second floor spandrel. The glass lites in storefront systems are normally larger than in punched window or strip window systems and may require relatively larger glass-to-frame clearances compared to clearances of smaller glass lites. If no sliding mechanism is provided between the horizontal mullions and the top spandrel, the storefront may experience the same story drift as the

Fig. 8-6. Example of a storefront window in a shopping mall

surrounding wall, depending on the flexibility of the caulking or sealant material used between the vertical mullions and the wall.

The construction of curtain walls is generally different from that of punched windows, strip windows, and storefronts in that the framing of curtain walls can be continuous over multiple stories and can constitute the entire exterior skin of the building as shown in Fig. 8-7. The glazing frames in curtain walls normally are attached to the building's structural system (frames and floors) using clip angles strong enough to carry the weight of the curtain wall and transfer it to the structure and transfer the out-of-plane lateral (e.g., wind) load on the curtain wall to the structure. Typical clip angles shown in Fig. 8-8 are used in stick-built construction of curtain walls to attach the vertical mullions to the structure such that the mullions may be continuous over two or more stories as needed.

In such stick-built construction, the mullions will deform as shown in Fig. 8-9 to accommodate building story drifts. In such a condition, the glazing frame will take the overall shape of a parallelogram and cause glass panes to translate and rotate to adjust to the deformed glazing frame shape. The glass-to-frame clearance therefore plays a significant role in the potential for glass damage. Fig. 8-10 shows a typical "dry-glazed" detail of a glazing frame in which the glass edge is held in place with rubber gaskets. The larger the clearance between the glass edge and mullion pocket wall, the larger the drifts that can be accommodated. In general, once the clearance is overcome through glazing frame deformation, and the glass corners bear directly on the metal, the probability of glass cracking and breakage will increase. Of course, different types of

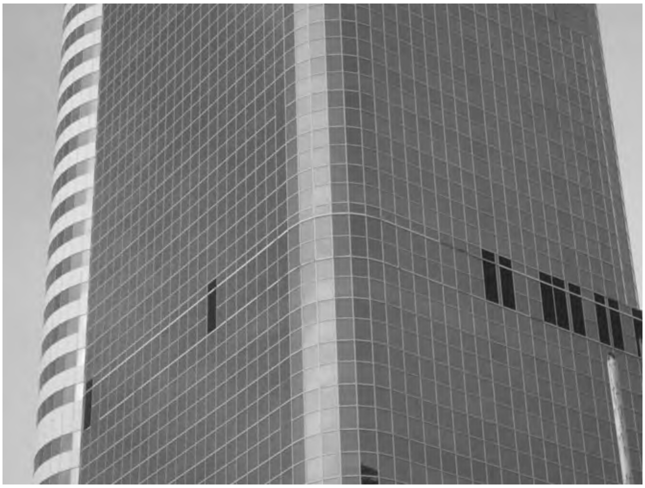


Fig. 8-7. Example of a curtain wall in a multistory building

Fig. 8-8. Example of clip angles attaching mullions to the building's structural frame

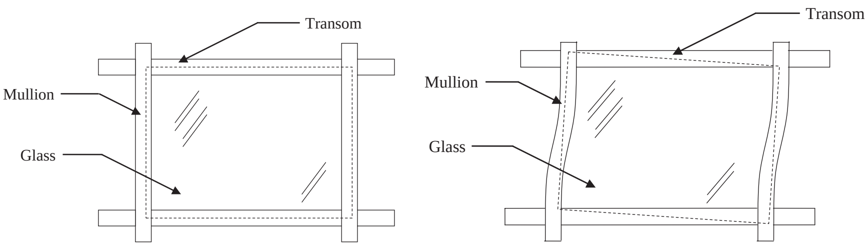


Fig. 8-9. Conceptual deformation of glazing frame and subsequent translation and rotation of glass pane

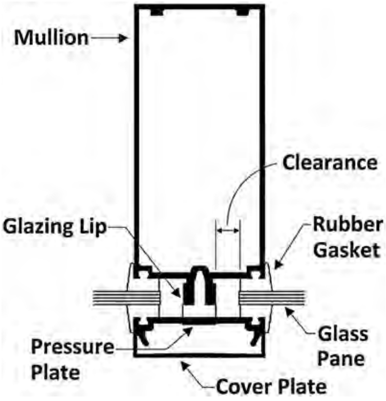


Fig. 8-10. Typical dry-glazed curtain wall detail

glass, such as annealed, heat strengthened, and fully tempered will have different strength and toughness when it comes to probability of damage to glass. According to ASTM (2004a), heat treatment of glass (e.g., heat strengthened or fully tempered) creates residual surface compressive stresses ranging from 10,000 to 18,000 psi (68.95 to 124.11 MPa), which increases the capacity of the glass. As a rough measure, heat-strengthened glass is twice stronger than annealed glass, whereas fully-tempered glass is four times stronger (GANA 2004).

As an alternative to stick-built construction, which requires attachment of the glazing frame to the structure followed by placement of the glass panes within the glazing frame and capture of the edges through mechanical clamping or use of structural sealant to adhere the glass edges to the glazing frame, the "unitized" system has recently become popular. In unitized systems (Fig. 8-11), glass is adhered to the glazing frame at the shop, and the prefabricated panel is shipped to the site for attachment to the building. In the more conventional unitized construction, each panel is attached to the top floor through bearing connections that allow the panel to hang from the edge of the top floor. Adjacent panels normally are attached to each other through vertical stack joints and, in some cases, horizontal stack joints that allow in-plane sliding of adjacent panels with respect to each other. Proper design of this curtain wall construction system allows accommodation of building story drifts without causing excessive glazing frame deformation. The result is that the glass panes are

Fig. 8-11. Example of a unitized curtain wall system under installation in a multistory building
Source: Courtesy of Shawn Li, ARUP; reproduced with permission

not expected to translate and rotate with respect to the glazing frame, thus minimizing glass-to-frame contact and reducing the potential of damage to glass (Memari et al. 2011b). The horizontal stack joints are in effect seismic isolation joints that allow the panels of one story to horizontally displace (slide) with respect to the panels of adjacent stories.

Although the predominant mechanism of attaching glass panes to glazing frames has been the dry-glazed system in the past (Fig. 8-10), in which the glass edges are held tight in glazing frame pockets with rubber gaskets under the clamping force of pressure plates, structural sealant glazing (SSG) has become a popular alternative (AAMA 1985, ASTM 2002). In SSG construction, the glass edge is adhered to the glazing frame through structural sealant (silicone) without the need to be mechanically held within the glazing pockets. Fig. 8-12 shows a typical SSG detail, and Figs. 8-13 and 8-14 show example applications of SSG systems on buildings. If only the two vertical edges of glass panes are adhered to framing using structural sealant while the two horizontal (top and bottom) edges are dry glazed, then the system is referred to as two-sided SSG, as shown in Fig. 8-13. If, however, all four sides are glazed using structural sealant, it is four-sided SSG as shown in Fig. 8-14.

When SSG is employed in stick-built construction, the racking deformation of the glazing frame causes the glass pane to accommodate such deformation because of the flexible silicone that attaches the glass edge to the glazing frame. In general, because the glass edge is not held within the glazing frame pockets, the glass edge or corners will not contact metal during racking movements and thus the probability of glass damage is reduced. Furthermore, if the gap between adjacent glass edges, which normally is filled with weatherseal sealant, is sufficiently wide (say 0.5–1.0 in. [12.7 to 25.4 mm]), then the probability of glass-to-glass edge or corner contact also will be reduced. Therefore, the effect of using SSG is

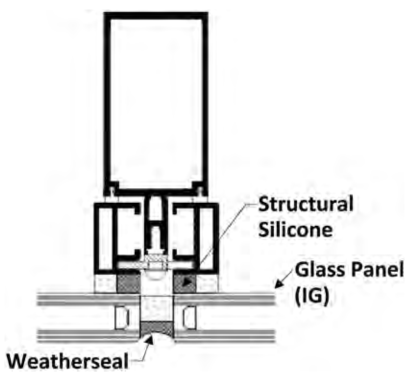


Fig. 8-12. Typical SSG curtain wall detail

Fig. 8-13. Example of a two-sided SSG curtain wall (capped horizontally and SSG vertically)

Fig. 8-14. Example of a four-sided SSG curtain wall

likely a reduction of the potential for glass damage (Memari et al. 2006a, 2011d). However, because the silicone will be subjected to large shear and tensile deformations during racking movement in stick-built systems, the deformation capacity of silicone (resistance to adhesive and cohesive failure) will be an important design parameter (Memari et al. 2011c).

It should be added that in unitized constructions where the system is shop-glazed, the SSG system normally is used instead of dry glazing. The combination of unitized construction of the glazing frame and shop glazing SSG system gives rise to a curtain wall system that is likely to have improved seismic performance compared with stick-built construction. Of course, many other parameters besides those affecting the seismic performance may have to be considered in developing objective and realistic comparisons among various systems and combinations of options.

Besides factors such as the type of glazing frame construction and attachment to building (stick built vs. unitized), glass pane to frame attachment type (dry glazed vs. SSG), and glass type (annealed, heat strengthened, or fully tempered), another parameter that affects the seismic response is the glass panel system itself. Aside from monolithic glass pane, laminated glass and insulating glass units are also commonly used in curtain walls and storefronts. The use of laminated glass in particular is desirable in seismic regions because the polyvinyl butyral (PVB) interlayer film will prevent glass shards from falling in case of cracking or fracture of any of the laminated glass lites (Behr 1998, Behr et al. 1995). The insulating glass unit is in general a heavier glass panel, and one of the panes can, in fact, be a laminated glass pane. The use of sealants and a spacer to attach the two panes to make up an insulating glass unit gives rise to a generally stiffer and tougher panel with larger in-plane strength compared with a monolithic or laminated glass pane. In general, the thicker the glass pane, the stronger will be its in-plane resistance (Memari et al. 2003).

Finally, besides the inherent material strength aspects, parameters that influence the induced seismic force should be considered. In general, the heavier the glass panels, the larger will be the induced out-of-plane seismic force on the panel and the force to be transferred from the glass panel edges to the glazing frame. Therefore, an insulating glass unit of the same perimeter dimensions as those of a monolithic glass pane will experience a larger out-of-plane seismic force. Needless to say, a glass panel with larger dimensions will experience a larger force and out-of-plane deflection compared to smaller panels.

Nonstructural components in buildings are generally thought of as being acceleration sensitive, drift sensitive, or both. Acceleration-sensitive components are those supported by one floor and not influenced by story drift. Office glass partitions, glass dividers in department stores, or glass railings that are entirely supported on the floor without attachment to ceiling or floor above can be thought of as acceleration sensitive only, where their design will be governed by the seismic-induced out-of-plane lateral loads based on the supporting floor acceleration. However, curtain walls or storefronts that span from floor-to-floor are affected by story drift, as well as floor acceleration. But because the main factor for seismic design of such systems is the drift requirement, they may be considered primarily drift-sensitive nonstructural components. In general, all components should be designed for acceleration-based seismic-induced forces, but not all are affected by story drift. Further discussion on force and drift design requirements is presented subsequently when explaining the code seismic design provisions.

8.3 BUILDING CODE SEISMIC PROVISIONS FOR DESIGN OF GLAZING SYSTEMS

Glazing systems constructed as punched windows, strip windows, storefronts, or curtain walls can be subjected to seismic-induced forces and the effects of story drifts during earthquakes. Seismic forces are generated because of floor accelerations, and their influence on glazing systems is more important in the out-of-plane direction. The seismic-induced force on any nonstructural component, in this case, a given glass panel, shall be determined based on ASCE 7-10 (ASCE 2010) according to the following equation (ASCE 7-10 Eq. 13.3-1):

$$F_p = \frac{0.4 a_p S_{DS} W_p}{\left(\dfrac{R_p}{I_p}\right)} \left(1 + 2\frac{z}{h}\right) \tag{8-1}$$

These are subject to the following upper and lower bounds (ASCE 7-10 Eqs. 13.3-2 and 13.3-3):

$$0.3 S_{DS} I_p W_p \leq F_p \leq 1.6 S_{DS} I_p W_p \tag{8-2}$$

where the parameters are defined as follows:

F_p = the horizontal seismic design force to be applied at the component's center of gravity and distributed relative to the component's mass distribution
S_{DS} = spectral acceleration at short period
a_p = component amplification factor
I_p = component importance factor
W_p = component weight
R_p = component response modification factor
z = height in structure at point of attachment of component with respect to the base
h = average roof height of structure with respect to the base

Although according to ASCE 7-10, the seismic force F_p shall be applied in at least two orthogonal directions in combination with other applicable service loads, for glazing systems the out-of-plane direction is the more critical direction. In general, seismic-induced force on relatively light glazing systems is not expected to govern over wind loads in determining glass thickness, which for wind is determined based on ASTM E 1300 (ASTM 2004b). Nonetheless, for large and heavy glass panels, seismic load also could be critical.

As an example of comparing seismic load and wind load on glass curtain wall, assume a 1.0 in. (25.4 mm) thick insulating glass unit made up of two ¼ in. (6.4 mm) thick lites of glass for the curtain wall on an office building in a high seismic area. To simplify this example, determine the seismic load F_p using the upper bound in Equation (8-2), i.e., $F_p = 1.6\ S_{DS}\ I_p\ W_p$. For this condition, assume $S_{DS} = 1.0$ for a high seismic region, $I_p = 1.0$, and for W_p, a unit weight of 3 lb/ft^2 (143.6 N/m^2) for ¼ in. (6.4 mm) thick architectural flat glass gives $W_p = 6$ lb/ft^2 (287.2 N/m^2). In that case, $F_p = (1.6)(1.0)(1.0)(6\ \text{lb/ft}^2) = 9.6\ \text{lb/ft}^2$ (459.6 N/m^2), say 10 lb/ft^2 (478.8 N/m^2). The minimum design wind load for the main wind-force resisting systems as well as cladding is 16 lb/ft^2 (766 N/m^2) (ASCE 2010). This example shows that the minimum design wind load is 60% larger than the maximum seismic load on a typical insulating glass unit in a high seismic region. This confirms the usual practice of designing glass for out-of-plane wind load and not for seismic loads.

However, the glazing system on the building envelope certainly will be affected by the seismic-induced floor displacements. The critical direction in this case is the in-plane direction, and the glazing system must be constructed such that it can accommodate the building seismic design drifts safely. According to ASCE 7-10, glass in glazed curtain walls, storefronts, and partitions shall satisfy the story drift requirement according to the following equation (ASCE 7-10 Eq. 13.5-1):

$$\Delta_{fallout} \geq 1.25 I_e D_p \text{ or } 0.5 \text{ in. (12.7 mm), whichever is greater} \qquad (8\text{-}3)$$

where

$\Delta_{fallout}$ = the relative seismic displacement (drift) at which glass fallout occurs from the curtain wall, storefront, or partition

D_p = the relative seismic displacement that the component must be designed to accommodate; D_p shall be applied over the height of the glass component under consideration

I_e = the importance factor

ASCE 7-10 provides the following three exceptions for cases in which the stated drift requirement need not comply:

1. Glass with sufficient glass-to-frame clearance as given by the following equation (ASCE 7-10 Eq. 13.5-2) to avoid physical contact between the glass and frame at design drift:

$$D_{clear} \geq 1.25 D_p \tag{8-4}$$

where

D_{clear} = relative horizontal displacement (drift) over the height of the glass panel under consideration that causes initial glass-to-frame contact. For rectangular glass panels D_{clear} is given by the following equation:

$$D_{clear} = 2c_1 \left(1 + \frac{h_p}{b_p} \frac{c_2}{c_1}\right) \tag{8-5}$$

where h_p and b_p are the height and width of the rectangular glass panel, respectively, and c_1 and c_2 are the clearances between the vertical and horizontal glass edges and the frame, respectively. Fig. 8-15 shows these parameters.

2. Use of fully tempered monolithic glass located no more than 10 ft above a walking surface in occupancy category I-III
3. Use of annealed or heat-strengthened laminated glass in single thickness with interlayer no less than 0.03 in. (0.8 mm) with glass perimeter mechanically captured in a glazing pocket and secured to

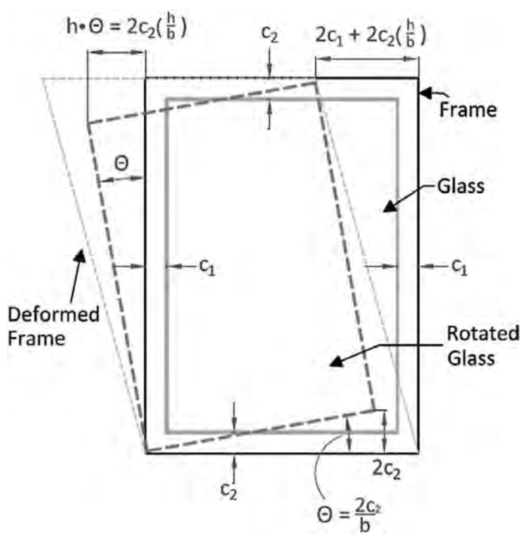


Fig. 8-15. Definition of geometric parameters

the frame by a wet-glazed gunable curing elastomeric sealant perimeter bead of 0.5 in. (12.7 mm) minimum glass contact width or other approved anchorage system.

ASCE 7-10 specifies that $\Delta_{fallout}$, defined as the drift causing a glass piece at least 1 in. squared (645 mm^2) in area to fall out from the curtain wall, storefront, or partition, shall be determined according to the dynamic cyclic racking test protocol described in AAMA 501.6 (AAMA 2009a, 2009b) or by engineering analysis.

In most applications of the aforementioned seismic provisions to glazing system design, glazing design professionals typically try to satisfy the seismic drift requirements by providing adequate glass-to-frame clearances to avoid glass-to-frame contact. These clearances vary, however, ¼ in. (6.4 mm) to ½ in. (12.7 mm) are typical values. An important reason for preference of glazing manufacturers and designers to design the systems based primarily on the first exception is the additional cost of carrying out AAMA 501.6 tests. Of course, because the first exception is primarily applicable to dry-glazed systems, as these are the systems that provide glass-to-frame clearance, SSG systems are perhaps more dependent on AAMA 501.6 test protocol or in some cases on other evidence (e.g., acceptable performance by similar designs) to show satisfaction of seismic drift requirements.

As an example of using Equation (8-5) for D_{clear} in exception 1, assume a glass panel with dimensions of h_p = 6 ft (1829 mm), b_p = 4 ft (1219 mm), and clearances of $c_1 = c_2$ = 3/8 in. (9.5 mm). In this case

$$D_{clear} = 2(3/8)(1+[6*12*3/8]/[4*12*3/8]) = 1.87 \text{ in. } (47.5 \text{ mm}) \quad (8\text{-}6)$$

D_{clear} = 1.87 in. (47.5 mm) means that a drift of 1.87 in. (47.5 mm) over a 6 ft (1829 mm) height of glass panel will cause the glass pane corner to contact the glazing frame within the pocket. For design, therefore, one would ensure the drift over 6 ft (1829 mm) height to be smaller than 1.87/1.25 = 1.50 in. (38.1 mm). To convert this drift to a drift over a story height, assume that this glass panel is part of a strip window system, such as the one shown in Fig. 8-16 with story height of 12 ft (3658 mm). Then the design story drift corresponding to the story height can be obtained as follows:

$$Dp \le D_{clear}/1.25 = (1.87''/1.25)*(12'/6') = 3.0 \text{ in. } (76.2 \text{ mm}) \quad (8\text{-}7)$$

In other words, the maximum design story drift for the glazing system to be acceptable is 3.0 in. (76.2 mm) over the full story height.

As another example, consider a storefront system shown in Fig. 8-17 with glass height of 9 ft (2743 mm) for which AAMA 501.6 test results are available and determine the maximum story drift for which this storefront

Fig. 8-16. Strip window for drift calculation

Fig. 8-17. Storefront window for drift calculation

is acceptable. Assume that the glass is placed on a storefront with floor-to-floor height of 13 ft (3962 mm) and that from AAMA 501.6 test results on this type of storefront with the same height glass the glass fallout drift is $\Delta_{fallout} = 3.0$ in. (76.2 mm) over the glass height of 9 ft (2743 mm). Assuming occupancy importance factor $I_e = 1.0$, the maximum design drift based on Equation (8-3) is as follows:

$$Dp \leq D_{clear}/(1.25I_e) = (3.0/[1.25*1.0])*(13'/9') = 3.47 \text{ in. } (88.1 \text{ mm}) \qquad (8\text{-}8)$$

In other words, the maximum design story drift is 3.47 in. (88.1 mm) over the full story height of 13 ft (3962 mm) for which this storefront is acceptable.

For those glazing systems that need AAMA 501.6 testing to determine $\Delta_{fallout}$, a commercial and certified laboratory must carry out the tests. In the following section, the AAMA 501.6 test protocol and a related one, AAMA 501.4 protocol, are explained.

8.4 MOCKUP TESTING REQUIREMENTS

Curtain wall and storefront systems and their components, including glass panes, framing system, and their attachments to buildings, vary greatly in materials, configuration, and design. Although for some large projects advanced analysis tools such as finite element modeling, may be used to evaluate the design parameters (e.g., Memari et al. 2007), in most cases, only out-of-plane deflections and perhaps stresses under wind-loading conditions are evaluated. For seismic-loading conditions where in-plane direction is generally the critical direction, generally accepted component capacity prediction equations as in other materials (e.g., steel, concrete, wood) are not available for glazing systems, and, therefore, testing often is used for performance evaluation. As it relates to seismic testing of glazing systems, two test protocols are available and often used, AAMA 501.4 and AAMA 501.6 (AAMA 2009).

AAMA 501.4 test protocol is designed to evaluate the behavior (e.g., failure modes) of curtain walls and storefront wall systems when subjected to a predefined displacement. In this test method, a mockup (test specimen) is subjected to a statically applied displacement of amplitude 0.01 times greater than adjacent story heights for three full cycles. Each cycle is defined as a full displacement in one direction, unloading, followed by full displacement in the opposite direction. All visual distresses, such as disengagement, framing distortion, sealant or glazing failure, or permanent deformation are recorded. If glass breaks and the cause is deformation or failure of supporting frame or the interaction of the glass and supporting elements, the specimen has failed the seismic test for the most part. Detailed pass/fail criteria that depend on occupancy category are given in AAMA 501.4. If the cause of glass breakage cannot be determined, the glass may be replaced and the test repeated one more time.

The mockup for curtain wall for the AAMA 501.4 test shall include at least two typical units in addition to the connections and supporting elements at both sides. Furthermore, the mockup shall include at least one vertical joint or framing member or both. The height of the mockup shall be at least the story height in single story buildings, whereas for multistory buildings, the mockup shall include at least two full stories in addition to the full horizontal joint. The curtain wall or storefront mockup shall include all full-size components of the same glazing frame material, glass type, details, method of construction, and anchorage as those used on the actual building.

Whereas AAMA 501.4 protocol focuses on characterizing the behavior of the mockup under the static racking displacement and its effect on air leakage resistance and water penetration resistance, AAMA 501.6 protocol determines the ultimate capacity in terms of glass fallout of the mockup. The intention of AAMA 501.6 is to determine the drift ($\Delta_{fallout}$) during a racking test associated with fallout of glass pieces of at least 1.0 in. squared (645 mm^2) as an ultimate limit state behavior.

As mentioned in Section 8.3 on seismic provisions of ASCE 7-10 with respect to glazing, if the glass-to-frame clearance (i.e., dry-glazed system) is not sufficient to avoid glass-to-frame contact under the design drift, then the acceptable performance of the glazing system must be established through testing. AAMA 501.6 addresses this need by determining $\Delta_{fallout}$ through a dynamic racking test in the form of a cyclic crescendo test. The mockup for this test shall include critical glass panels with highest potential for glass fallout. For example, the mockup should include panels with largest glass area, glass panels with smallest thickness (if glass panes with different thicknesses will be used), the most vulnerable glass type (if different types will be used), the most vulnerable glazing system (if different glazing systems will be used on the building), panels with smallest glass-to-frame clearances, and panels with smallest height-to-width ratio. The connections used to attach the test specimen shall replicate the support conditions for the glazing system that will be mounted on the building.

The loading protocol for the AAMA 501.6 test consists of incrementally increasing displacement amplitude applied as a crescendo as shown in Fig. 8-18. The figure shows the concatenated serried steps consisting of "ramp-up" intervals and "constant amplitude" intervals. At each step, the displacement is increased by the constant increment of 0.25 in. (6.4 mm) Each step shown consists of eight cycles, four during the ramp-up and four during the constant amplitude intervals. The crescendo test is to be performed at a frequency of 0.8 Hz for displacements of 3.00 in. (76.2 mm) or less and 0.4 Hz for displacements greater than 3.00 in. (76.2 mm). The protocol states that the crescendo test shall continue until one of the following conditions is reached: (1) a piece of glass at least 1.0 $in.^2$ (645 mm^2) in area falls out; (2) the drift index (defined as the drift at top of the glass panel divided by the glass panel height) over the height of the glass panel is at least 0.1 (i.e., 10%); or (3) a maximum racking displacement of 6.0 in. (152.4 mm) is reached. This defines when the test should be stopped. Under condition (1), the drift at which glass fallout occurs is noted as $\Delta_{fallout}$.

As examples of carrying out AAMA 501.6 test on a curtain wall, consider some of the tests carried out in the Building Components and

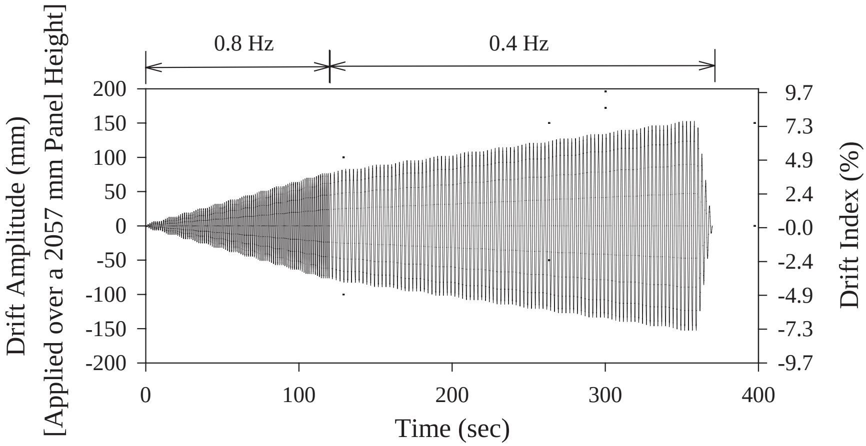


Fig. 8-18. Drift time-history for AAMA 501.6 dynamic racking crescendo test

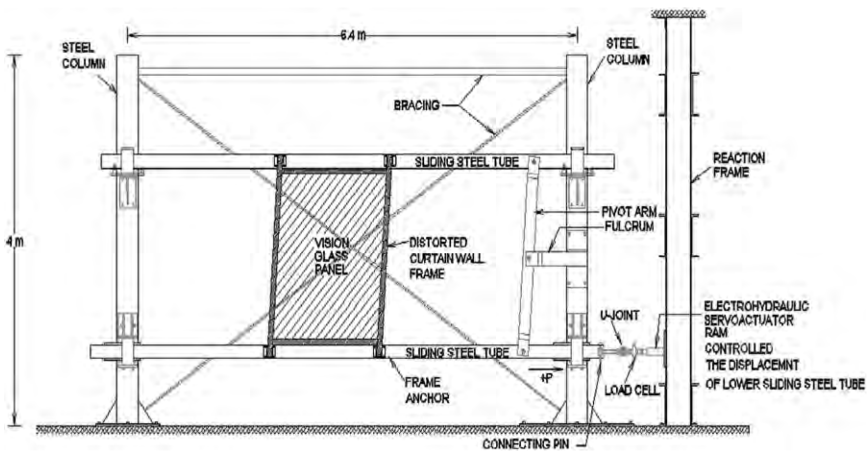
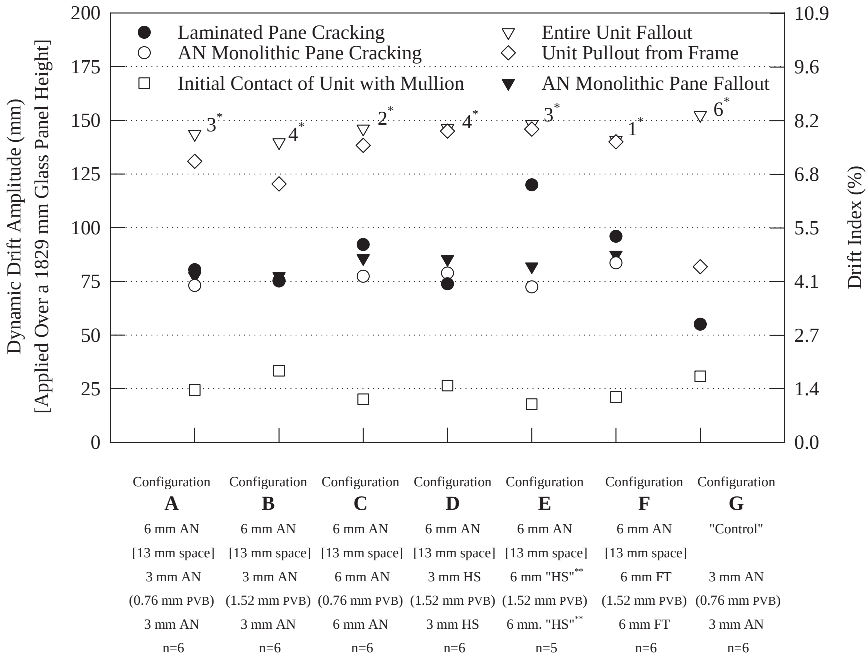


Fig. 8-19. Dynamic racking test facility schematic for curtain wall mockups

Envelopes Research Laboratory (BCERL) at Penn State University (e.g., Memari et al. 2003). Fig. 8-19 shows the schematic of the test facility with specimen attached to the facility. The results of testing several types of insulating glass units mockups with dry-glazed stick-built framing are plotted in Fig. 8-20, which shows the drift corresponding to different damage states including cracking and glass fallout.

Because current AAMA 501.6 is the only test protocol that is recognized by the building code to evaluate the satisfaction of seismic provisions for glazing systems, the protocol has also been used for evaluating innovative glazing design or system concepts to reduce and minimize seismic-induced



*Indicates the number of specimens that exhibited no glass fallout by the end of the Crescendo Test.

**Configuration E specimens were actually FT (surface compressive prestress of 76.5 MPa (11,100 psi)).

Fig. 8-20. Example AAMA 501.6 racking test results

glass damage or injuries. As an example, proof of concept for a seismically isolated glazing system where the panels in one story slide with respect to panels in adjacent stories was carried out using AAMA 501.6 (Brueggeman et al. 2000). Another use of this protocol has shown how glass shards after breakage of glass in racking tests can be held together by application of polyethylene terephthalate (PET) film (Memari et al. 2004). Application of film to glass is an accepted retrofit method (e.g., used in California to retrofit schools). Still another use of the AAMA 501.6 test protocol has shown the effectiveness of rounding the corners of glass lites to reduce the cracking potential or increasing the drift capacity of the glazing system (Memari et al. 2006b).

8.5 CLOSING REMARKS

The objective of this chapter was to introduce the basic information regarding seismic behavior and design and testing of glazing systems under earthquake loading conditions. The chapter provided a brief definition of various glazing systems and components and reviewed the performance of glass in past earthquakes. Various parameters that are important for and influence the seismic performance of glazing systems also were identified and discussed in detail. The ASCE 7-10 seismic provisions were discussed and simple examples provided. Finally, the AAMA 501.6 seismic test requirements were mentioned and example test results presented. Throughout the chapter some of the relevant and recent references for additional information were suggested.

On the basis of the material presented, it should be clear that for safe and serviceable design of glazing systems under earthquake loading conditions, a glazing design professional with structural engineering training should be involved, preferably from the early conceptual design stage. Such a design professional can help the architect in choosing the most appropriate glazing system for seismic and wind load effects and other serviceability criteria. The choice of a glazing system type, for example, dry-glazed versus SSG, can have a bearing on overall project cost, not just because of design/fabrication/construction aspects, but also because of the possible need for testing. For example, by providing sufficient clearance between glass edge and framing, the seismic requirements of drift can perhaps be satisfied for dry-glazed systems without the need for AAMA 501.6, but this may not be the case for the choice of a SSG system.

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CHAPTER 9

DESIGN OF CURTAIN WALLS TO RESIST IMPACT AND BLAST

Mohammad M. Ettouney

This chapter deals with blast effects on building envelopes in general and curtain walls in particular. The chapter first presents qualitative methods that address blast effects. Then greater space is devoted to discussing quantitative methods. As with any engineering-related subject, quantitative methods include demands, analysis, and design issues. The chapter also presents some popular retrofit methods that are used for blast design. And because both quantitative and qualitative methods invariably need decision-making tools, the chapter will discuss the subject and then will end with a discussion of some ongoing and future issues that relate to blast effects on building envelopes. Fig. 9-1 shows the content discussed in this chapter and how it fits together.

9.1 QUALITATIVE CONSIDERATIONS

Rapid evaluation of the blast adequacy of building envelopes is needed in many situations, for example, if a large stock of buildings needs security evaluation and a need exists to prioritize mitigation measures for these buildings so that resources are spent efficiently and in a timely manner. In such situations, the decision maker may choose to evaluate risk of blast to building envelope in a rapid, simple, efficient, yet accurate manner. Tools exist specifically for such rapid evaluation, see for example FEMA 426 (2003), FEMA 452 (2005), FEMA 455 (2009), and DHS (2011a). These tools qualitatively evaluate risk of blast threats to the building envelope. Actually these tools also evaluate risk of blast threats to other important building components (such as structural systems and

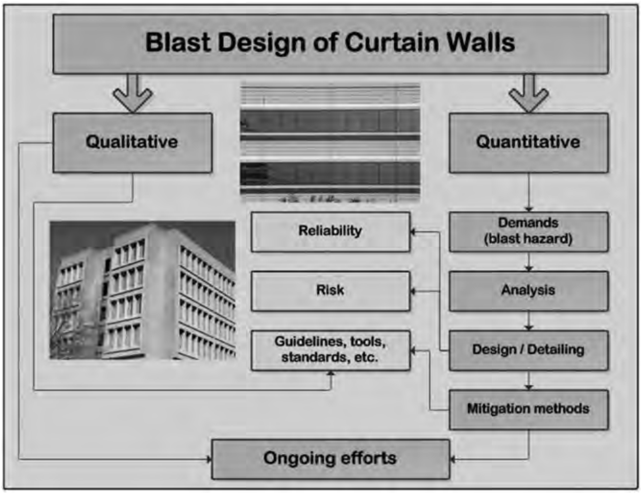

Fig. 9-1. Contents of the chapter

Mechanical, Electical, and Plumping MEP systems). Additionally, the integrated rapid visual screening (iRVS) tool, which was introduced in DHS (2011a) estimates risks of natural hazards such as earthquakes, wind, and flood. Examples some qualitative methods to estimate the blast worthiness of envelope attributes are as follows:

- **Envelope window system:** Window systems can affect blast worthiness. They are rated from most to least worthy as follows: (1) no windows; (2) punched windows, see Fig. 9-2; (3) glass and metal frames (curtain walls); (4) ribbon, see Fig. 9-3; and (5) point supported, see Fig. 9-4.
- **Window area:** The window area ratio is defined as the ratio of the window area to the total wall area, where walls are assumed to provide greater protection than windows to occupants. Thus, as the window area ratio increases, the blast worthiness of the envelope decreases. See Fig. 9-5 for examples of how the window area ratio increases for typical buildings.
- **Type of glazing:** Glazing type directly relates to blast worthiness. Glazing types are most to least blast worthy as follows: (1) laminated, (2) with security film, (3) tempered, (4) heat strengthened, and (5) annealed.
- **Envelope construction type:** Type of envelope construction also directly relates to blast worthiness. Construction types from most to least blast worthy are as follows: (1) cast-in-place reinforced concrete (Fig. 9-6); (2) curtain wall systems; (3) precast panels;

Fig. 9-2. Punched windows
Source: FEMA (2009)

Fig. 9-3. Ribbon windows
Source: FEMA (2009)

Fig. 9-4. Point-supported windows
Source: FEMA (2009)

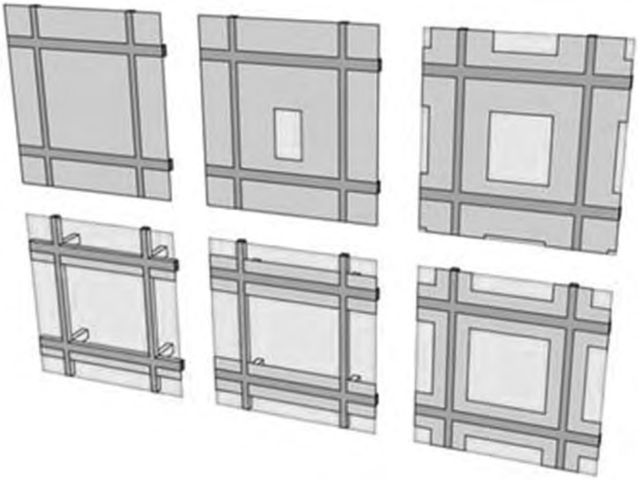

Fig. 9-5. Examples of window area ratios
Source: FEMA (2009)

(4) reinforced masonry; (5) massive reinforced masonry; (6) light metal frames; and (7) slender unreinforced masonry (Fig. 9-7).

The previously mentioned qualitative methods estimate risk components (threats, vulnerabilities, and consequences) of envelope (and other building components) by observing envelope attributes and estimating risks based on these observations.

Fig. 9-6. Cast-in-place reinforced concrete envelope
Source: FEMA (2009)

Fig. 9-7. Slender, nonreinforced masonry envelope
Source: FEMA (2009)

Note that the resulting risk estimates of these tools have been thoroughly validated, see FEMA (2003) and DHS (2011a and 2011b). They have been used satisfactorily by many entities, such as police departments, and several private and public users.

9.2 QUANTITATIVE CONSIDERATIONS

Unlike the qualitative methods for assessing blast risks, quantitative evaluations are much more involved, as expected. The following sections will briefly discuss major aspects of quantitative blast evaluations. Because of the limited scope of this chapter, only short summaries are presented. For detailed descriptions, the reader should refer to more indepth documents such as FEMA (2003) and FEMA (2005).

9.3 DEMANDS: BLAST PRESSURES

The main source of blast pressures on curtain walls, or building envelopes in general, is the detonation of bombs near the building under consideration. Fig. 9-8 shows the sequence of such detonation. When the

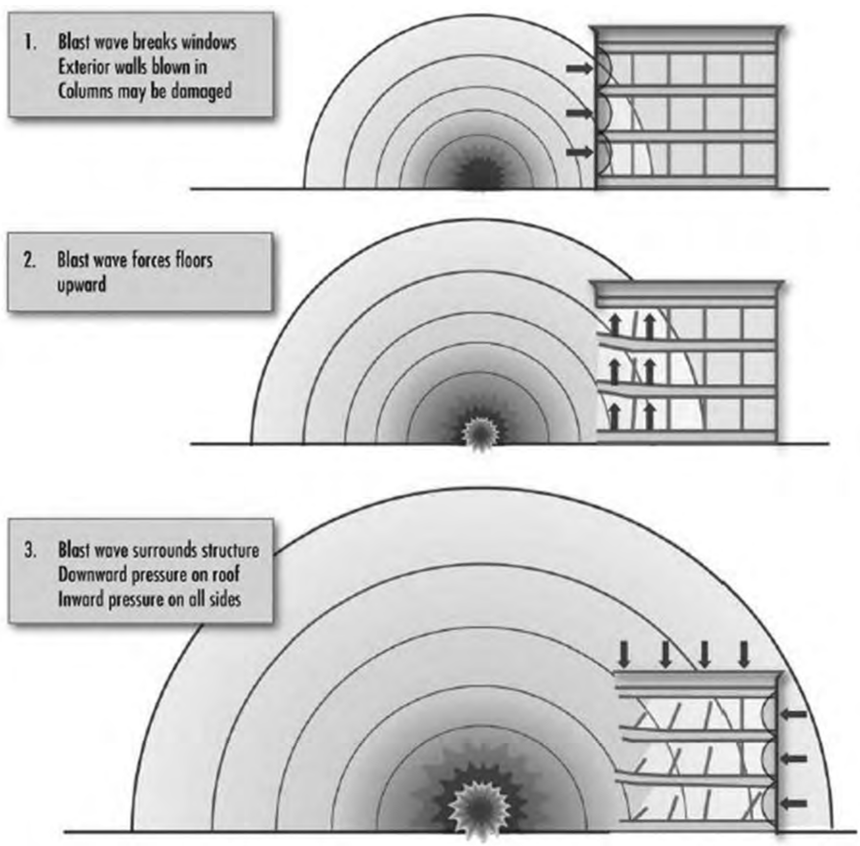

Fig. 9-8. Propagation of blast waves
Source: FEMA (2003)

blast wave from a detonation arrives at the building envelope, it affects the building in ways that are consistent with the design of the envelope system. As the blast pressure engulfs the building, it starts affecting the roof and finally has an effect on the envelope of the back side of the building. Clearly, all sides of the building envelope must be designed with blast pressures in mind.

Two main factors affect the severity of blast pressures. Obviously the weight of the explosive, *W*, is one of these factors. The other factor is the distance between the explosive and the building envelope, *L*. Such a distance usually is referred to as stand-off distance. The response of the building depends on the combination of *W* and *L* as shown in Fig. 9-9 and Table 9-1. Note that Fig. 9-9 gives a relationship between explosive weight

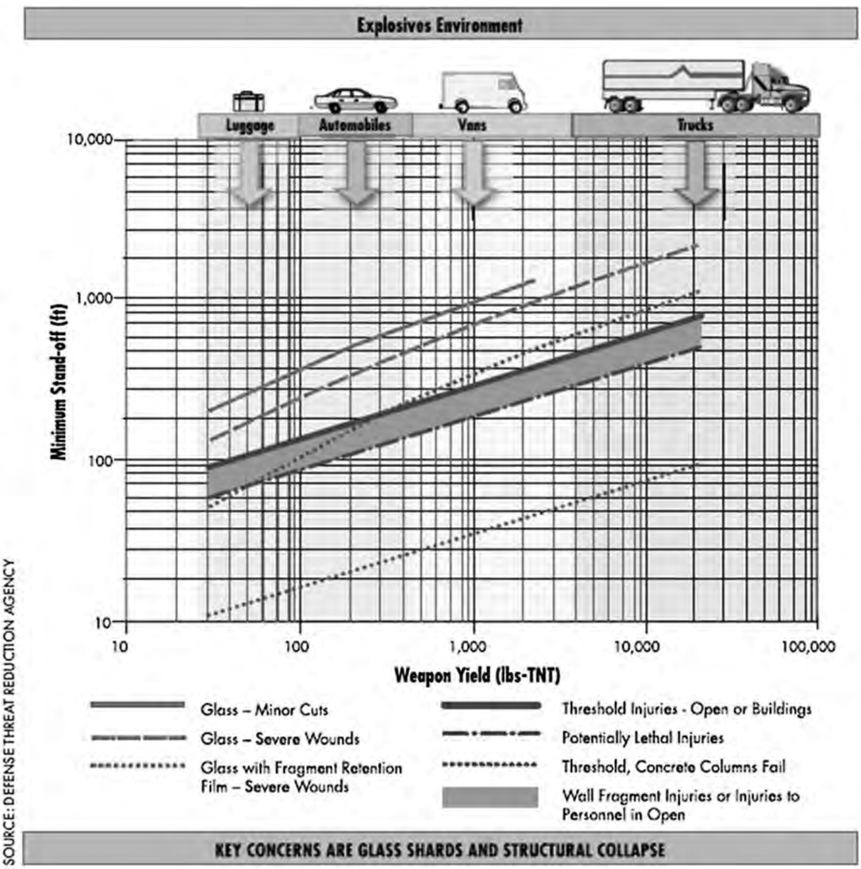

Fig. 9-9. Factors affecting responses to blast pressures
Source: FEMA (2003)

Table 9-1. Responses of Building Components to Different Blast Levels (FEMA 2003)

Damage	Incident Overpressure (psi)
Typical window glass brakage	0.15-0.22
Minor damage to some buildings	0.5-1.1
Panels of sheet metal buckled	1.1-1.8
Failure of concrete block walls	1.8-2.9
Collapse of wood framed buildings	Over 5.0
Serious damage to steel framed buildings	4-7
Severe damage to reinforced concrete structures	6-9
Probable total destruction of most buildings	10-12

W, distance (minimum stand-off) *L*, and different potential types of damages to different important building components, including glass-breaking effects and threshold of reinforced concrete column failure. Table 9-1 shows qualitative relations between pressures and the qualitative damage these pressures might produce. Obviously, the building envelope components are most sensitive to blast hazard. The building responses that are described in Fig. 9-9 are based on experience and are mostly qualitative. For objective design of building envelopes, estimates of blast pressures are needed.

A simple method of estimating blast pressures on building envelopes is by using Fig. 9-10. Note that, like Fig. 9-9, Fig. 9-10 shows a relationship between explosive weight *W*, distance (minimum stand-off) *L*, and an estimate of the resulting pressure. These pressures are obviously an estimate and can vary greatly depending on many factors, including type of terrain and locality, etc. As before, the pressure is a function of *W* and *L*:

$$p = f(W, L) \tag{9.1}$$

Fig. 9-10 shows graphically the relationship in Equation (9.1). For a given *W* and *L*, the pressure *p* can be estimated. Note that the figure gives only a scalar estimate of the pressure. Blast pressures are time-dependent quantities that are functions of *W* and *L* and many other factors such as site condition, type of explosives, and other factors. In most situations, the design of building envelopes depends on the wave form of blast pressures. Many methods can be used to estimate blast-pressure wave forms. Some of these methods are wave tracing, computational fluid dynamics, and empirical methods.

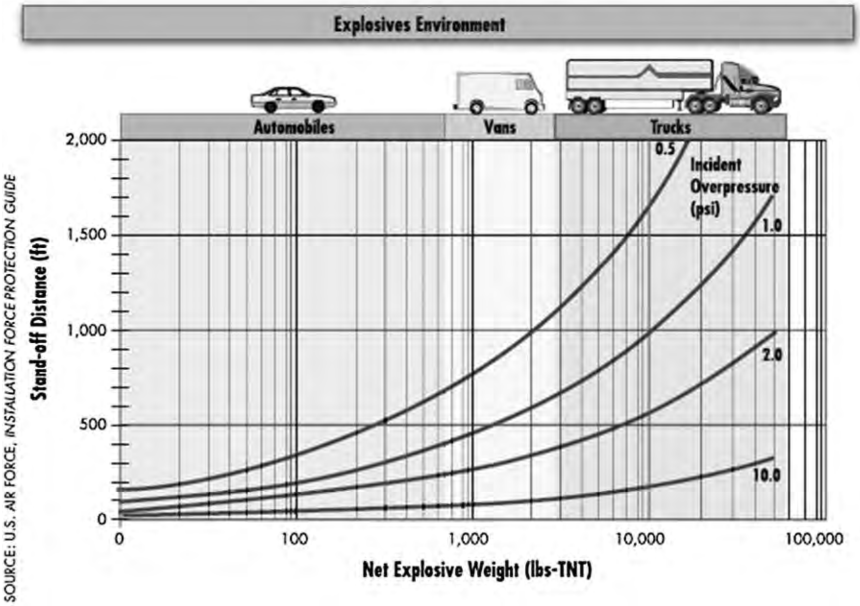

Fig. 9-10. Estimations of blast pressures
Source: FEMA (2003)

Generally speaking, blast wave forms consist of two phases: positive and negative phases, as seen in Fig. 9-11. Most envelope designs are affected by the positive phase. However, negative phase also can be important when designing for rebound of different components. In addition to the pressure wave form, the total impulse of the blast event is of importance in design. The impulse, I, is given by the following equation:

$$I = \int p(t)dt \tag{9.2}$$

where t is the time variable.

Depending on the duration of the blast wave form and the dynamic properties of the system under consideration, the relative importance of p and I during the design process differ. Thus, considering both p and I during blast design is important.

9.4 DIRECT ANALYSIS METHODS

Given the time-dependent nature of blast pressure, $p(t)$, a quantitative analysis of the curtain wall response needs to be dynamic. The simplest

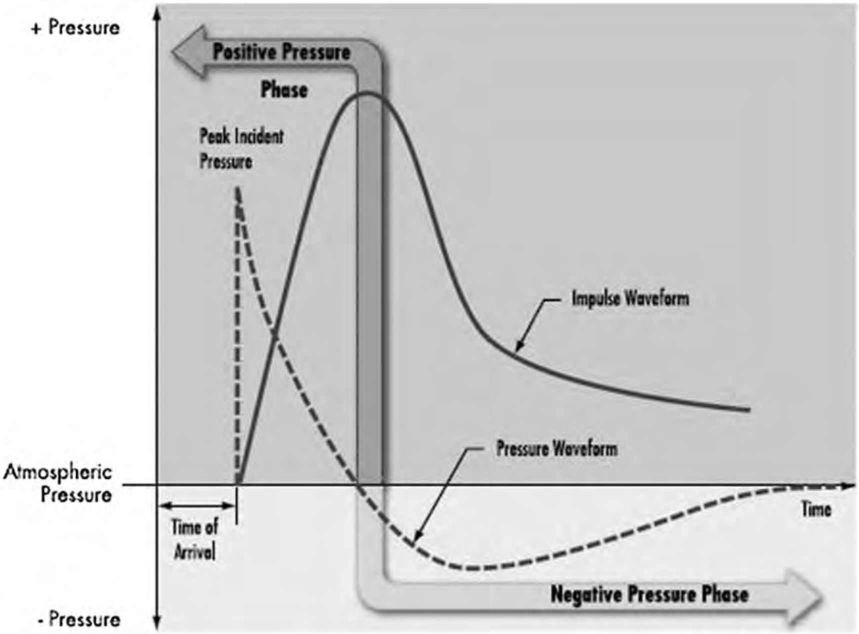

Fig. 9-11. Blast-pressure and impulse wave forms
Source: FEMA (2003)

method is to use single degree of freedom (SDOF) modeling. The governing equation for SDOF is

$$m\ddot{u} + c\dot{u} + ku = p(t) \tag{9.3}$$

The equivalent mass, damping, and stiffness are m, c, and k, respectively, while the equivalent acceleration, velocity, and displacement are $\ddot{u}$, $\ddot{u}$, and u, respectively. The equivalent properties depend on the system being modeled. The resulting $\ddot{u}$, $\dot{u}$, and u are then used in the design and detailing processes.

SDOF works best when it models simple components such as individual panes of glazing. For this reason, using SDOF to model a curtain wall system in a serial fashion is customary. This entails modeling glazing first as an SDOF, then transferring the computed reactions onto the supporting frame that is modeled in turn as an SDOF. This process continues until the reaction forces on the supporting structural system are computed. The method is summarized in a step-by-step approach as follows:

1. The sequential SDOF modeling of glazed façade applies the blast design implies that we are modeling: (1) glazing layup, (2) the

supporting mullions, and (3) framing and connections, independently without accounting for any interactions between the three components. The sequence starts by modeling the glazing layup as an SDOF that is subjected to blast pressure. The computed dynamic reactions are then applied to an SDOF model that represents the supporting mullions. The computed dynamic reactions of this model finally are applied to an SDOF model that represents the framing and connections. The dynamic reactions computed from the analysis of this final model are used in designing the structural system, if needed. The motions and internal forces that are computed from these three SDOFs are used to design the different components of the glazed façade.
2. The peak blast pressure and impulse, idealized as a linearly decaying triangular pulse, is input into glazing analysis software, along with the window dimensions, to determine the required glazing make-up and the bite size required to satisfy performance criteria.
3. The resulting edge-reaction forces are then used as input to design the mullions and frames to which the glazing lites are attached.

The SDOF modeling has several drawbacks such as the following:

- Irregular geometries: SDOF can produce poor results if the curtain wall is made up of irregular geometries,
- Potential to be too conservative: The sequential applications of SDOF to the system components can produce conservative results,
- Arbitrary limit states: SDOF can only handle component limit states, it cannot handle system limit states, and
- The model is unable to predict important localized effects.

Because of these limitations, using the finite elements method (FEM) to analyze curtain wall response to blast pressures is an alternate analysis method that can provide more accurate results. Fig. 9-12 shows a typical example of an FEM model for curtain walls. Note that the glass plates are modeled using a concentrated mass that is attached to the supporting frames via a set of radial springs. The frames are modeled as linear beams. The whole assembly is then supported on a set of anchors that connect it to the rest of the building's structural system.

Several blast design software programs can help designers. For example, the designer may use a combination of methods used in government-produced and -sponsored computer software such as the following:

- Window Lite Analysis Code (WINLAC),
- Window Glazing Analysis Response and Design (WINGARD), and
- Window Fragment Hazard Level Analysis (HAZL).

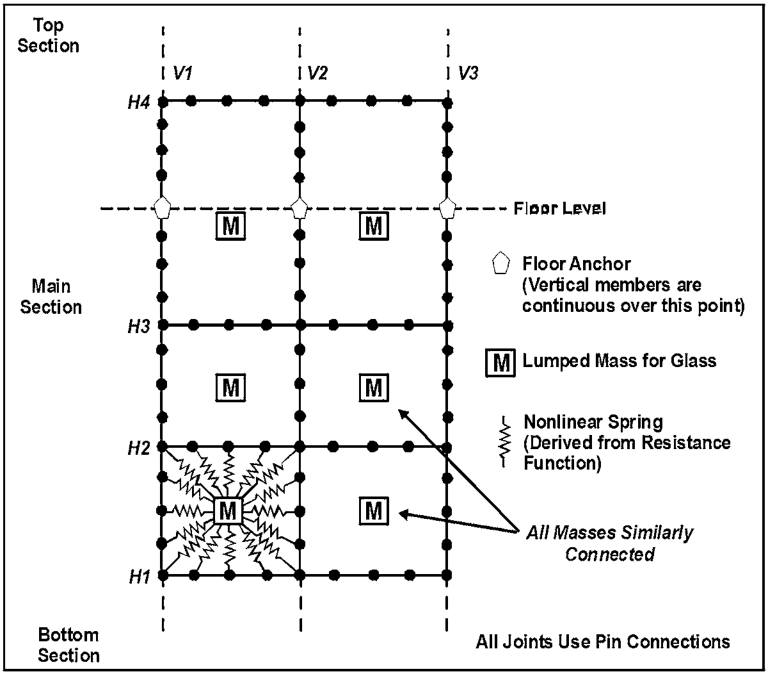

Fig. 9-12. Typical FEM of a curtain wall
Source: FEMA (2003)

9.5 ANALYSIS-DESIGN METHODS

Direct analysis methods, such as SDOF and FEM, are helpful for analyzing most blast dynamics problems. When the engineering properties of envelope systems are well defined, such as elastic limits, and acceptance criteria of such physical envelope systems are simple, such as ductility or angle of rotation limits, using direct analysis methods can be fairly straightforward. However, given the complexities of blast dynamics as it intersects with physical building envelope systems, these direct analysis methods can become difficult to apply. In such situations, additional layers of analysis, on top of the direct analysis method, might be needed to simplify the designer's level of effort. These additional layers of analysis are called analysis-design methods, because they aim to reduce design effort. The following sections address three analysis-design methods: glass-breaking acceptance criteria, P-I diagrams, and fragility of glass breaking.

9.5.1 Glass-Breaking Acceptance Criteria

When glass fails under blast pressure, the resulting shards fly into the room. The level of human injuries resulting from these flying shards relates the locations of the fallen shards. Fig. 9-13 illustrates the limits of fallen shards, while Table 9-2 shows the relationship between those locations and protection and hazard levels. Some of the software analysis programs that were described in the last section can aid the designer in direct evaluation of these protection levels for a given blast hazard.

9.5.2 P-I Diagrams

Another analysis-design method is known as the pressure-impulse (P-I) method. The P-I method is based on a set of curves, which are generated for the system under consideration. Each combination (P, I) that produces a limit state of interest for the system under consideration produces a point on the P-I curve. Thus the P-I curve can be considered as a dividing curve in the pressure (P)–impulse (I) space between the system state below and the limit state of interest above.

The P-I curves are generated a priori. Then they are used to reach the needed decisions as follows:

1. For a given system, compute the controlling pressure (P) and impulse (I) combination (P,I).
2. To evaluate whether the system is below or above a limit state, look at the pertinent P-I curve, and

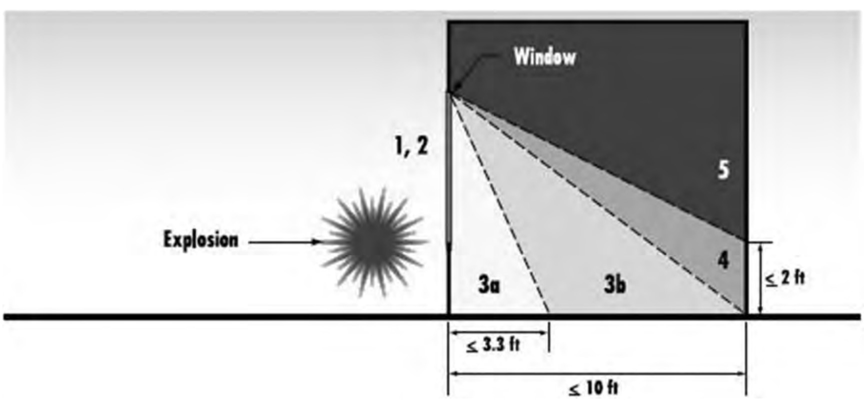

Fig. 9-13. Glass performance levels
Source: FEMA (2003)

Table 9-2. Glass Breakage Protection versus Hazard Levels (FEMA 2003)

Performance Condition	Protection Level	Hazard Level	Description of Window Glazing Response
1	Safe	None	Glazing does not break. No visible damage to glazing or frame
2	Very High	None	Glazing crack but is restrained by the frame. Dusting or very small fragments near sill or on floor acceptable
3a	High	Very Low	Glazing cracks. Fragments enter space and land on floor no further than 3.3 ft. from window.
3b	High	Low	Glazing cracks. Fragments enter space and land on floor no further than 10 ft. from window.
4	Medium	Medium	Glazing cracks. Fragments enter space and land on floor and impact a vertical witness panel at a distance of no further than 10 ft. from window at a height no greater than 2 ft. above the floor.
5	Low	High	Glazing cracks and window system fails catastrophically. Fragments enter space and land on floor and impact a vertical witness panel at a distance of no further than 10 ft. from window at a height no greater than 2 ft. above the floor.

a) If the (P,I) combination is above the P-I curve, such a (P,I) combination would produce a state in the system beyond the P-I limit state.
b) If the (P,I) combination is below the P-I curve, such a (P,I) combination would produce a state in the system below the P-I limit state.

An illustration of the P-I concepts is shown in Fig. 9-14.

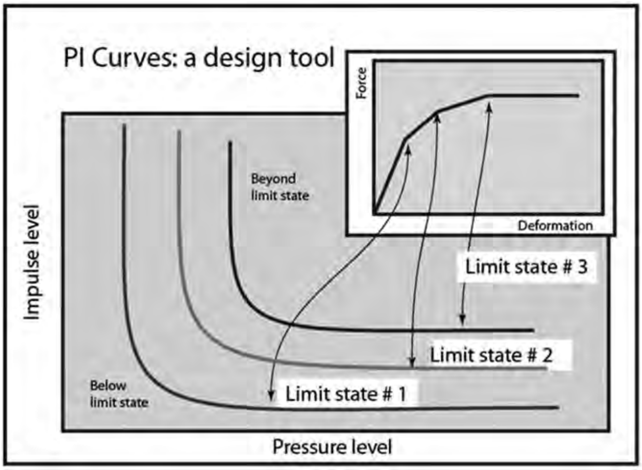

Fig. 9-14. Illustration of P-I diagrams

9.5.3 Fragility of Glass Breaking

Because of higher uncertainties regarding when glass breaks, sometimes a probabilistic approach to decision making is desirable. To aid in such situations, glass-breaking fragilities are used in the design process. Fragility curves define the probability of the occurrence of a certain limit state (a given number of breaks per thousand or BPT) for a given system (specific make of glass) resulting from a given specific demand (axial stress, for example). BPT relates to glazing performance as follows:

- Smaller BPT indicates stricter or higher performance.
- BPT is usually defined by the building owner.

Using fragilities produces probabilities of BPT. Acceptable probabilities using a fragility curve are defined by the engineer of record or project specifications. Fig. 9-15 shows typical fragilities of structural breakage.

9.6 DESIGN OF BLAST-RESISTANT SYSTEMS

Different components of the window system need different considerations for blast protection. Fig. 9-16 shows some considerations for blast protection of a typical window. The figure shows that the glazing needs to have strong attachments to the supporting mullions. In turn, the mullion system needs to hold the fractured glazing in place.

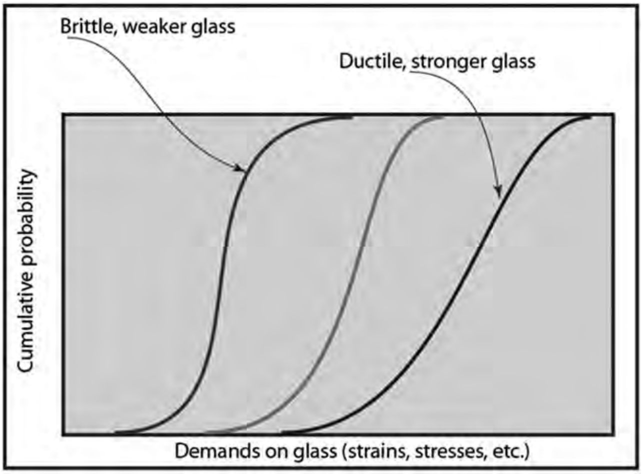

Fig. 9-15. Fragilities of glass breaking

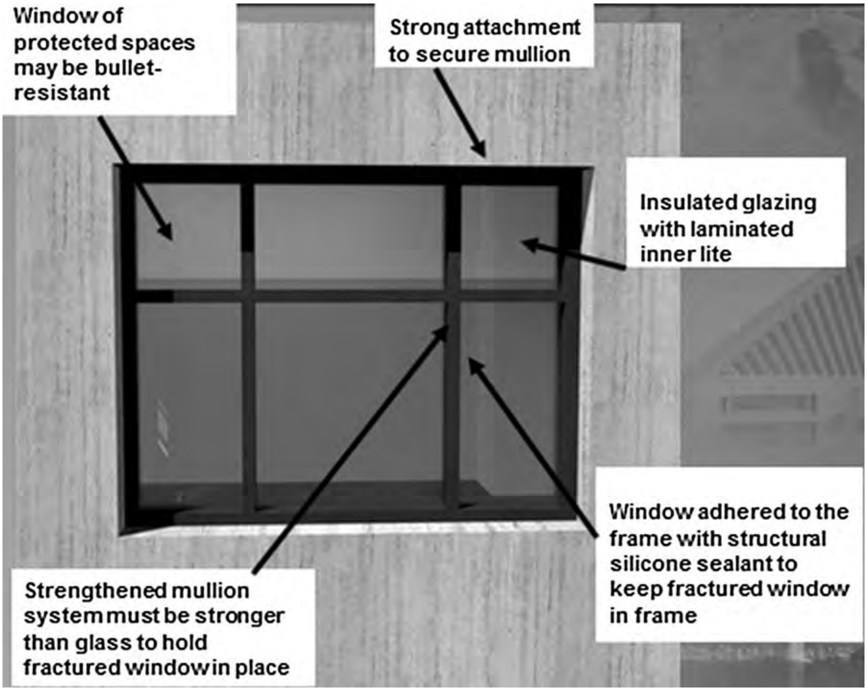

Fig. 9-16. Blast considerations for window system
Source: FEMA (2003)

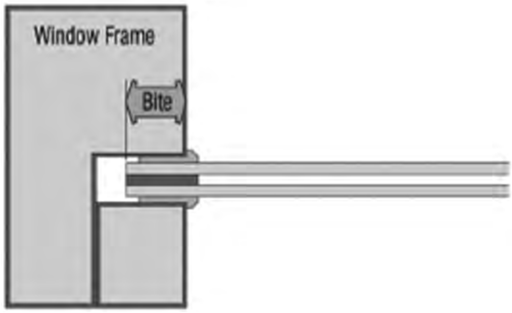

Fig. 9-17. Definition of window bite
Source: FEMA (2003)

The mullion design needs to accommodate the reactions from glazing as they occur in response to blast pressures. These connections must include a mechanical bite (Fig. 9-17) and structural silicone joints. Adequate bite detailing is important for blast-worthy windows. Because the glazing experiences flexural and tensile forces at the support due to blast loading, the bite needs to be well detailed to resist such forces and transmit them to the supporting window frame.

A major issue in designing a blast-worthy mullion system is that the connections must be at least as strong as the mullions themselves. Metrics for designing a mullion system are usually ductility or rotations of the mullions themselves. These design metrics are computed using the SDOF or FEM methods that were discussed earlier.

A popular design philosophy known as balanced design calls for the behavior of the façade system (glazing, frames, mullions, anchorage to supporting walls, etc.) to be balanced while mitigating the hazardous effects of flying debris in an explosive event (FEMA 2003). As such, the walls, anchorage, and window framing should fully support the capacity of the glazing material selected. Achieving a balanced design results in an efficient system and avoids premature failure of any envelope components.

9.7 MITIGATION SYSTEMS

This section explores some popular envelope blast mitigation systems. Some of these systems are used for curtain wall mitigation. Others are used for retrofitting noncurtain wall systems (such as nonreinforced masonry and steel stud systems). Even though nonreinforced masonry and steel stud systems technically are not considered curtain wall systems, this section includes them for completeness.

9.7.1 Security Film

One potential blast mitigation/retrofit measure for glazing is a security film attached to glazing. Generally speaking, the minimum thickness of such a film is 7 mil, while lesser film thicknesses might be used if validated by testing. Attaching films to glazing ranges in efficiency and cost as follows:

- Least effective and most cost-effective is to cover clear glazing area only.
- Both efficiency and cost increase when the glass, including bite (edge to edge), is covered with dry installation (dry glazed).
- Again, efficiency and cost increase with wet installation (wet glazed), where film is attached to framing via liquid sealants (silicone).
- Finally, mechanical attachment can be most effective (Fig. 9-18).

Note that as mitigation effectiveness of the security film increases, costs also increase.

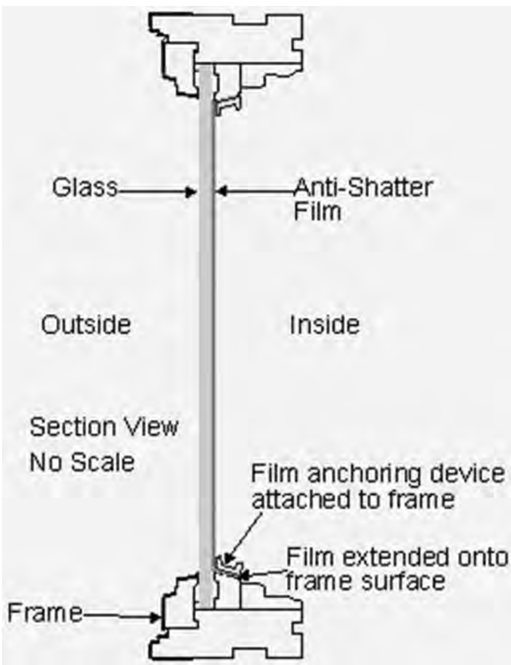

Fig. 9-18. Mechanical attachment of security film
Source: FEMA (2003)

9.7.2 Blast Curtains

Blast curtain systems, as the name indicates, is a curtain system that, when installed behind a window, will act as a catcher of shattered glazing when the building is subjected to a blast pressure. The system is made of fibers with high-tensile properties and is attached to the supporting wall. When the glazing is subjected to blast and fractures, the blast curtain will then transfer the blast load to the wall system through well-designed anchor points. Thus the wall system needs to be strong enough to resist the postulated reactions at these anchor points. Note that the curtains can be opened for inside cleaning of the window; however, during such activity, no blast protection is provided. Fig. 9-19 shows a typical blast curtain system.

9.7.3 Retrofits of Nonreinforced Masonry

Nonreinforced masonry walls perform poorly during high-demand events such as earthquakes or blast events. Therefore, for new construction, the recommendation is to avoid using unreinforced masonry walls in the case of a blast design requirement.

For existing construction, a frequently used retrofit method is to attach a system that is efficient in tensile capacity to the wall. A popular method

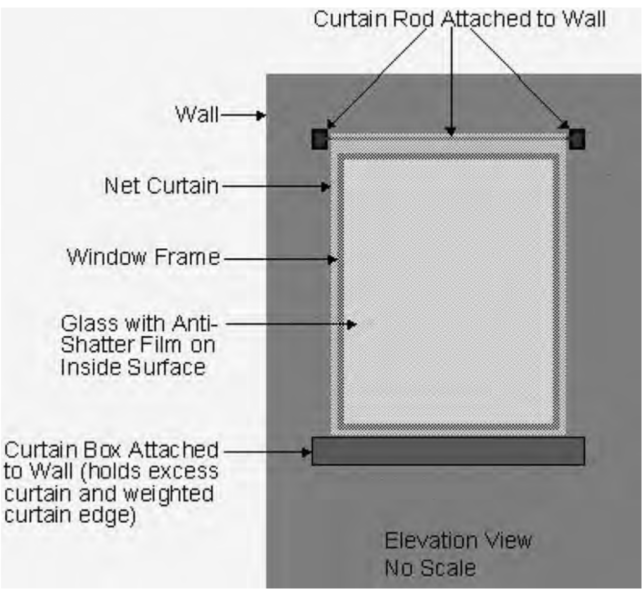

Fig. 9-19. Blast curtain system
Source: FEMA (2003)

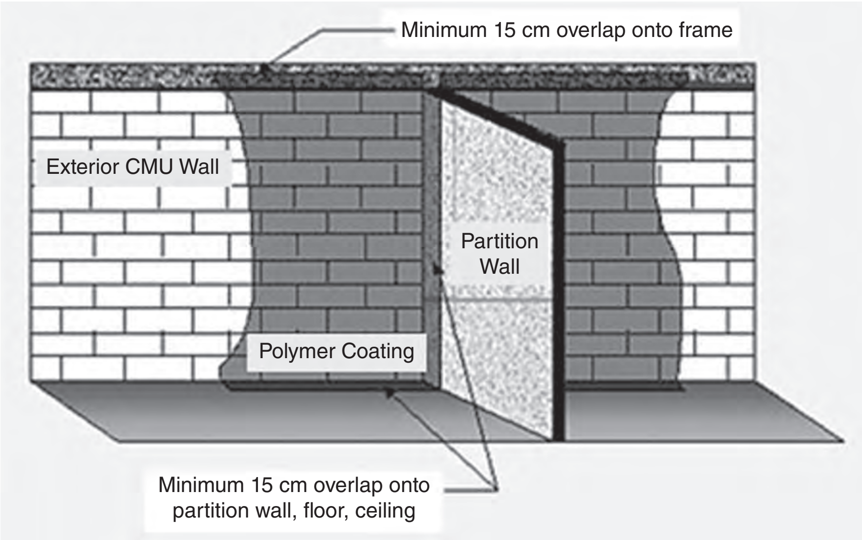

Fig. 9-20. Mitigation method for nonreinforced masonry
Source: FEMA (2003)

is to spray a polymer material on the wall. Such a spray-on can improve both in-plane and out-of-plane behavior (Fig. 9-20). Other types of materials that can be used are geotextile fabric, shortcrete, and steel studs.

9.7.4 Steel Stud Walls

Strong and highly ductile steel stud wall systems can be used for blast-resistance. Such a system can be used both for retrofitting existing walls and for new construction. The steel studs (Fig. 9-21) need to be at least 18-gauge studs. The cladding in front of the studs requires at least a 4 in. cover of stone, brick, masonry, or concrete. If forced entry protection is required in addition to blast protection, the cladding needs to be at least ¼ in. A36 steel plate.

9.7.5 Other Measures

Perhaps the most efficient blast mitigation system for glazing is simply to use laminated glazing. This is particularly true for new construction. When using laminated glazing, using well-designed connections to the supporting frame is essential, as discussed.

Other mitigation methods include the use of rigid or flexible catch bar. To be used effectively, the glazing needs to be designed so that it is

Fig. 9-21. Steel stud blast system
Source: FEMA (2003)

held together in response to a blast event. This can be achieved by using security film, or high-capacity laminated blast glazing. If the glazing system is disengaged from its support due to blast pressure, the catch bar will prevent the glazing from flying into the room and harming occupants.

9.7.6 Governing Design Documents

Several guidelines and standards can be of help in designing envelope systems to withstand blast effects. An example of these documents can be found in DoD-UFC (2007). American Society of Civil Engineers (ASCE) is working on a blast design standard. This standard has not been published yet as of writing of this chapter.

In many situations, owners can provide their own design requirements and methods. In such situations, effective coordination between the architect or engineer and the owner is needed.

9.8 DECISION-MAKING TOOLS

This section discusses different decision-making tools and methods that are used by practitioners when designing for blast loading. These tools include reliability, risk, resilience, and life-cycle analysis.

9.8.1 Reliability Analysis

Reliability analysis aims to study the interrelationship between capacity C and demand D of a particular item, or assembly of items, due to a particular hazard. Formally, reliability can be expressed as follows:

$$R = p(D > C) \tag{9.4}$$

where $p(x)$ is the probability of x. Most current engineering designs are based on some form of reliability treatment. This includes most current designs of curtain walls and building envelopes in general. Such methods allow for accurate decisions regarding safety; however, as a decision-making tool, it might not be sufficient, because it does not account for consequences.

9.8.2 Risk Assessment

Risk management is another popular tool for decision makers (DHS 2009, NRC 2010). The subject of risk management includes several categories, including risk assessment, risk communication, and risk treatment, among others. This section discusses briefly risk assessment of curtain walls. Other categories of risk are beyond the scope of this chapter; for further information see Ettouney and Alampalli (2012a, 2012b).

Risk assessment is concerned with the evaluation of risk for a given situation due to a particular hazard. Risk itself is a function of three variables: hazard H, vulnerability V, and consequence C. These variables can be independent or interrelated. Functionally, risk can be expressed as follows:

$$Ri = f(H, V, C) \tag{9.5}$$

Hazard H, can be defined as the hazard, or event of interest. Vulnerability V can be defined as the capability, or lack thereof, of the system under consideration to resist H. The consequence C is a measure of the potential consequences of the system being exposed to the hazard. Clearly, risk is a superset of reliability in that not only is it a measure of capacity and demands, but it is also a measure of the consequences of the interrelationship between capacity and demand.

Tools that prescribe risk assessment due to blast events are available, such as FEMA (2005), DHS (2011a), and DHS (2011b). These tools were developed by the United States Department of Homeland Security Science and Technology Directorate/Infrastructure Protection and Disaster Management Division (US-DHS S&T/IDD 2012).

9.8.3 Resiliency of Assets

Resiliency is an emerging decision-making tool that estimates the capability of an asset or community to recover from an abnormal event (such as an earthquake or blast event; NIAC 2009). This section focuses on asset resiliency, which can be defined as

$$Re = g(R_1, R_2, R_3) \tag{9.6}$$

where

R_1 = Measure of the robustness of asset protection. It includes protective measures, mitigation measures, and redundancy.

R_2 = Measure of how quickly the asset can recover from the event under consideration. It includes reparability, contingency planning, and recovery coordination.

R_3 = Measure of the different resources that can be used. It includes training, critical product stockpiles, information sharing, emergency coordination, response time, and crisis stabilization.

The propensity of a building envelope to resist a blast is clearly a factor in asset resiliency. Currently two tools estimate asset resiliency: DHS (2011a) and DHS (2011b).

9.8.4 Life Cycle Analysis

Life-cycle analysis (LCA) is another emerging decision-making tool that pertains to curtain walls as they are subjected to blast events. The main idea of LCA is to estimate the costs and benefits of a particular decision over the life span of the subject matter. The decision would then be based on such LCA, rather than on immediate cost–benefit considerations. Obviously, such an analysis is not an easy task. Currently, the only tool that accommodates such an LCA for curtain walls and building envelopes is DHS (2011b).

9.9 FUTURE DEVELOPMENTS

As of this writing, three major developments are ongoing in this field. Two of these three developments include the aforementioned ASCE blast design standard and DHS (2011a). The third development is a performance-based design tool for building envelope developed by the US DHS-S&T/IDD (DHS 2011b). The tool includes several building attributes such as security (blast, chemical, biological, abd radiological [CBR]), and ballistics); safety (seismic, wind, and flood); energy considerations of the envelope system; environmental considerations; and durability considerations. The tool enables the owner or the owner's representative to

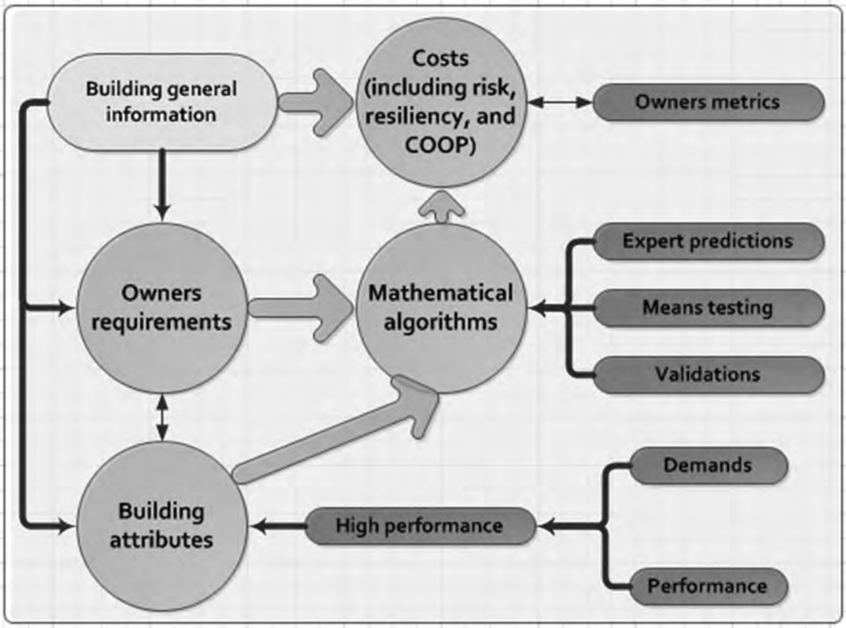

Fig. 9-22. Components of the Owners Performance Report (OPR) tool

prescribe any combination of demand and performance levels. The resulting outcomes of such prescribed demand and performance levels are then computed by the tool in the form of owner's metrics. The owner's metrics include resiliency and continued operations, risk level, energy and environmental footprints, and an assortment of life-cycle costs.

The computational blocks of the tool are obviously fairly complex as can be seen in Fig. 9-22. However, when completed, the tool would offer building owners and their representatives the means to produce an efficient, multihazard building envelope that can accommodate several building attributes, including blast effects, simultaneously.

9.10 CLOSING REMARKS

Designing curtain walls, or building envelopes in general, to resist blast impact is an important subject and a difficult one. These difficulties include (1) establishing the demands, such as blast temporal and spatial distributions; (2) establishing capacities, such as behavior of envelope components (glazing, frames, connections, etc.) or the integrated systems that combine these components; (3) performing different analyses that relate the demands (a) in the capacities in (b) to produce the expected performance of the component, or system, under consideration; and finally (4) different decision-making processes that consider all pertinent aspects to reach optimal solutions.

This chapter tried to highlight many of these difficult issues and briefly illustrate potential methods to address those difficult issues and achieve safe yet cost-effective solutions. Obviously, more indepth treatments of those difficult issues are needed. For such indepth understanding, the reader may wish to consult the reference list of this chapter as a starting point.

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CHAPTER 10

INNOVATIVE FAÇADE DESIGN AND PRODUCTS

Wilfried Laufs, Ph.D., P.E., and Erik Verboon

This chapter gives a brief overview of recent technologies that have entered or are beginning to enter the market of innovative façade applications from a façade engineering consultant's perspective. The chapter ends with a look out toward useful future research activities that will advance building envelope design in the progressively more digital and increasingly energy-conscious 21st century of building envelope design.

How can "innovation" in façade engineering and design be defined in a meaningful, forward-looking way? The answer might be to look beyond traditional ways of design. Whereas fundamental physical principles generally stand firm and unchanged over decades, an abundance of existing knowledge and technical strategies from other scientific disciplines exists that modern façade engineering has been able to adopt in recent years, and, as a result, has been able to advance the curtain wall and building envelope design industry considerably. This chapter summarizes such recent trends as well as new developments in enclosure design that have helped to advance modern façade design and products from the practical perspective of a façade consultant.

A first aspect is linked to energy-saving strategies for building enclosures, closely connected to the performance of façades and façade glazing. The second aspect focuses on transparency and translucency as such and how new transparent materials other than glazing have entered the marketplace. The third aspect of innovation is inspired by the building information modeling process (BIM) and can be summarized under heaDIgs such as "parametric modeling" and "digital fabrication." These tools have been associated with the ability to design and fabricate more complex and irregular building skin geometries, essentially allowing designers to create free-form shapes that can be handled and built by the advanced community of façade contractors. The chapter ends with a summary identifying future research needs.

10.1 HIGH-PERFORMANCE ENVELOPES: PASSIVE SYSTEMS

Common to high-performance building envelopes is the intent to minimize the building's energy consumption. The building envelope acts as the filter between often drastically different indoor and outdoor conditions, and its goal is to minimize energy transfer between these two conditions, or, in other words, to avoid heat loss in colder seasons to the outside, minimize heat gain to the inside during the warmer months, or manage temperature differences over the course of a day or year, effectively flattening upper or lower temperature peaks (Fig. 10-1). Passive systems or strategies are designed to use the free energy from the sun and wind to help provide the necessary levels of comfort on the interior—as opposed to active systems (described later in the chapter), where an input of energy from some source is needed for to condition the interior space. In the realm of building envelopes, it is commonly perceived that passive systems remain relatively static and do not respond to any particular condition over the course of a day or seasons, whereas active systems are designed to respond to an ever-changing climate and external conditions.

An increasing amount of new building designs (and retrofits of existing buildings) aim to meet or exceed performance guidelines set by local

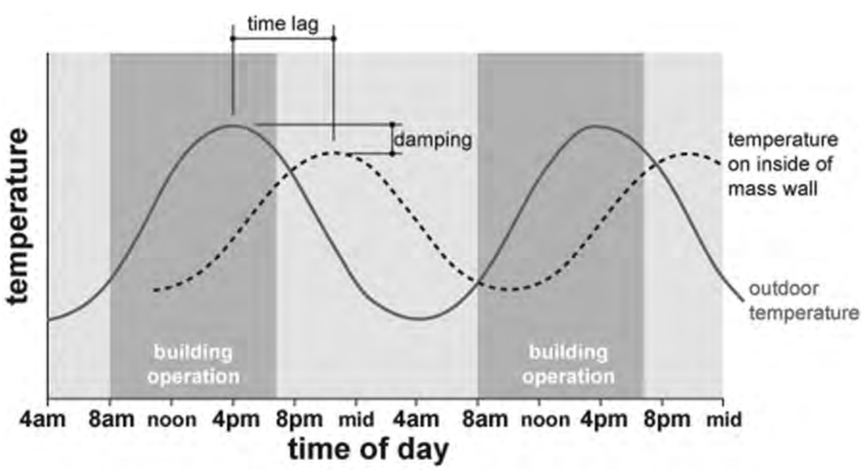

Fig. 10-1. Thermal lag with associated thermal damping

energy codes and building rating systems, such as the USGBC's LEED rating system or the Middle East's ESTIDAMA rating system, where energy efficiency of building envelopes together with day-lighting performance and embodied energy play an important part of the evaluation. The more traditional, fully glazed building, incorporating single-pane glass within a nonthermally broken frame no longer achieve the comfort and energy-efficiency levels the industry is looking for. This is as a result of a recent shift toward more contemporary, energy-efficient products and methods of design as described in the following sections.

10.1.1 Thermal Bridging

Thermal bridges are localized "bridging areas" in the building envelope that allow local heat conduction to occur, which is unfavorable with regards to energy consumption. Because heat flows through the path of least resistance, thermal bridges can contribute to poor energy performance. A thermal bridge is created when materials create a continuous path across a temperature difference, in which the heat flow is not interrupted by thermal insulation.

Thermal bridging is best explained by the "water bucket analogy" (Fig. 10-2): A bucket with water-tight thick walls and a single small hole cannot stop water from escaping the bucket through the hole, just like energy entering or leaving the building volume through small interruptions in the insulation around the building skin, "bridging" both sides of the building envelope. One element of façade engineering consulting is to design façades that minimize thermal bridging and, if thermal bridges cannot be fully avoided at times (for example in load-carrying local metal tongue plates for external attachment of façade elements), minimize their energy impact and study local condensation risks.

Conventional practice still does not always sufficiently tackle thermal bridging. For example, concrete balcony cantilever slabs without external

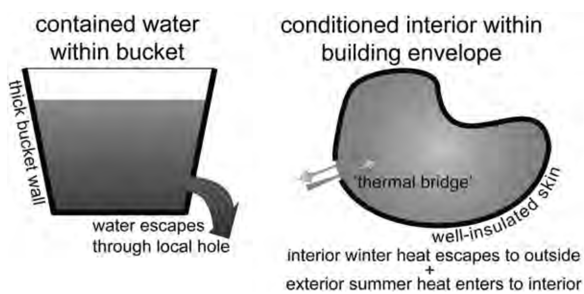

Fig. 10-2. Thermal bridging described with locally punctured water bucket analogy

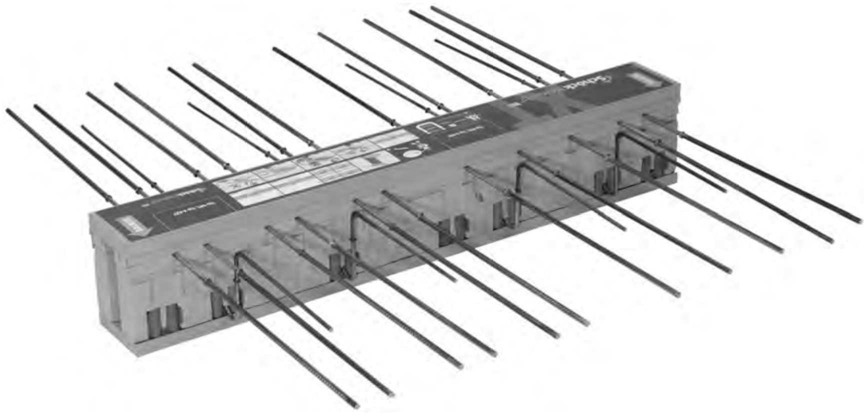

Fig. 10-3. Example of integrated thermal break product for concrete balcony slabs (Schock 2013)
Source: Courtesy of Schöck Canada Inc.; reproduced with permission

insulation or internal thermal breaks such as Schöck Isokorb (Schöck Innovative Baulösungen 2013; Fig. 10-3) transfer a significant amount of heat or cold into the inside, causing increased heating or cooling energy demands and risk of condensation and the potential for mold. So even though the phenomenon of thermal bridging has been known for a long time, in the author's practical experience this aspect plays a key role for modern façade design and retrofit, where many details and building envelope details still do not sufficiently avoid thermal bridging in building skins. Fully thermally broken window frames for example remain key to achieving energy-efficient curtain walls (Fig. 10-4).

10.1.2 High-Performance Glazing Solar Coatings

Higher performance in glazing units is most commonly achieved by means of coatings applied to the glazing surface, either as "hard coating" or "soft coating." The coating takes advantage of the human eye's limited perception of visible wave-lengths from 380 to 780 nm by reducing as little visible light as possible, or in other words not affecting the amount of visible light entering the space (often measured as VLT or visible light transmittance). The coatings focus on long-wave lengths (>780 nm), also referred to as IR or infrared, by reflecting and absorbing the considerable solar energy contained in these long wave lengths (Fig. 10-5), hence reducing the overall solar gain that enters the building and cooling costs during the warm months. These coatings create what is commonly known as low-e, or low-emissivity, glass.

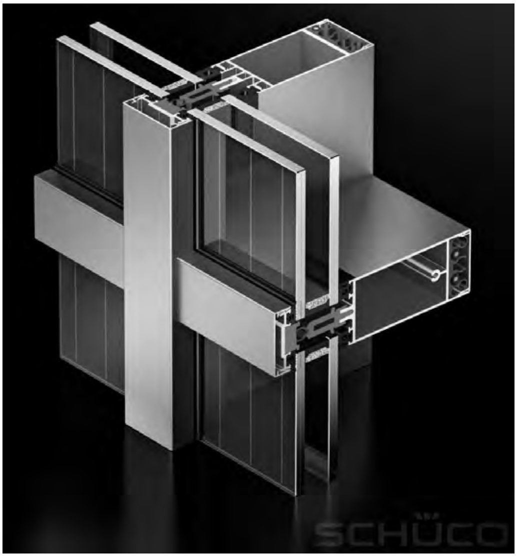

Fig. 10-4. Schüco FW50 Thermally Broken Frame (Schüco 2013)
Source: Courtesy of Schüco-USA; reproduced with permission

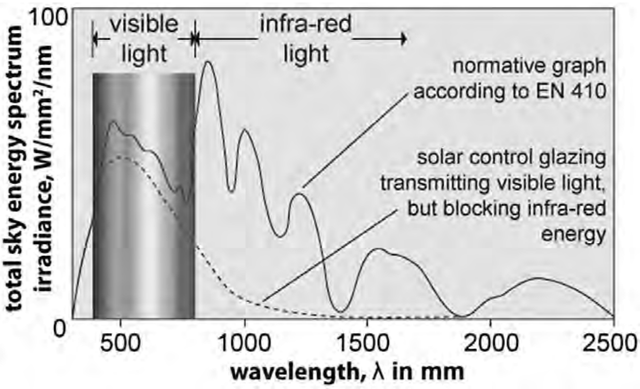

Fig. 10-5. Total solar spectrum of the sky vs. visible light range—functionality of solar coating

Both hard and soft solar coatings tend to tint the visual glazing appearance of façade elements slightly, mostly toward slightly green, blue, or gray. This is due to the fact that their complementary colors on the long-wave spectrum of visible light are slightly filtered out, hence intensifying the green, blue, and gray colors within the glass melt. The subsequent color rendering of the glass is something for architects to decide during the mockup phase glazing sample review for a project (in addition to a glazing product's external reflectivity that defines the amount of light as reflectance of the sky).

When choosing a high-performance glazing system the objective is often to pick a glass type that maximizes the transmittance of visible lite (high VLT), while minimizing the percentage of solar radiant energy that is transmitted through the assembly, known as the solar heat gain coefficient (low SHGC). This ratio of VLT to SHGC is called the light-to-solar-gain ratio, or LSG. New soft coatings that recently have entered the market (by Glass Troesch and others) are using a new coating inside the insulating glass unit (IGU) on both face two and three simultaneously, achieving a highly selective VLT to SHGC ratio of 0.28 to 0.51. This means that despite a low total energy transmittance through the glazing, a relatively large amount of visible light still enters the inside space.

"Hard Coating" Historically, chemical vapor deposition (CVD) is the older of two main technologies used to manufacture low-e glass. In the CVD process, vapor directed to the hot glass surface reacts to form a ceramic coating. The resulting solar coating often is referred to as "hard coat" and is also known as "pyrolytic." Because the coating is covalently bonded to the glass, hard coat low-e glass is extremely durable, yet it does not reach sufficiently low solar heat gain coefficients (SHGC) while maintaining high levels of visible light (VLT). For this reason, together with fabrication and durability advantages, soft coatings tend to be specified more often in recent façade engineering design. However, pyrolytic (hard coat) low-e glass can be tempered, cut, tinted, bent, and used in single-pane applications unlike glass with soft coatings. Hard-coat low-e, one of the earliest coating types, reduces heat loss compared with clear glass and allows a high level of solar heat gain. It is most appropriate in climates where solar heat gain is desired.

"Soft Coating" Magnetron Sputtering Vacuum Deposition (MSVD) or "sputtering" is the more recent technology used to manufacture highly selective metal solar coatings. Less durable than hard coatings, the low-e coating is applied to the outer insulated glazing panel on the side facing the space between the panes (#2 surface) and is thus protected from environmental factors and mechanical damage. In MSVD, a metal or ceramic target bombarded with ions releases atoms to form a thin coating on a sheet of glass. The resulting low-e product is often called "soft coat" or "sputtered." Less scratch resistant than its hard-coat counterpart, soft coatings need to be protected within the IGU, which explains why modern façades should be specified as IGU rather than single or laminated glazing to activate the high-performance values of soft coatings fully (Fig. 10-6). Soft coatings also require special storage and handling to

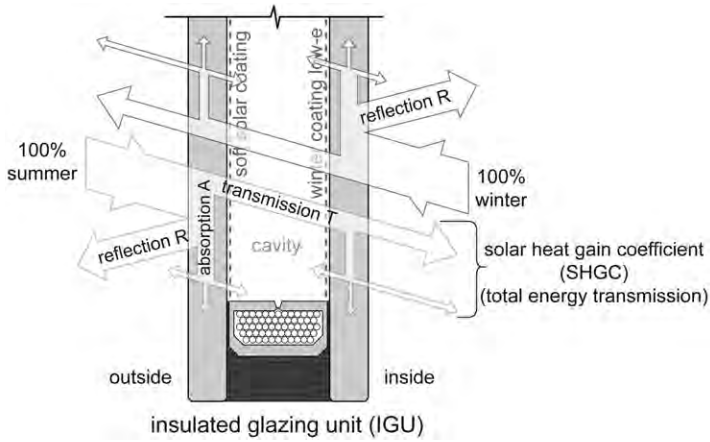

Fig. 10-6. Summer and winter energy flow through glazing with combination of soft coatings

prevent damage to the coating, which has been addressed successfully in recent years.

10.1.3 High-Performance Insulation

Decreasing the thermal conductivity (or u-value) of the building envelope through the use of insulating materials helps reduce heating and cooling energy and hence also helps reduce the building's carbon dioxide footprint (Pfundstein et al. 2008). The lack of high-insulation materials can lead to increased summer heat gains (requiring cooling) and winter heat loss (requiring heating). Even small areas of heating or cooling bridges can affect energy flow of the façade significantly (see section 10.1.1). The thermal conductivity, λ, is a common physical parameter of insulating materials (Table 10-1).

The key to these high-performing insulating materials is that they have low densities (material mass per occupied volume). This low density implies a high porosity, where a large amount of voids lowers thermal conductivity (air pores being a high-performance insulator). Some common material examples follow.

Aerogel with λ = 0.017 to 0.021 W/(mK) (0.010 to 0.012 Btu/[hr ft F]) Aerogel entered the façade market some years ago, being a very lightweight, highly porous, solid nonbrittle material, primarily manufactured from Silicate (SiO_2) and derived from a gel in which the liquid component of the gel has been replaced with a gas. Aerogel is an

Table 10-1. Classification for Material Insulation Degree Related to Thermal Conductivity (Schueco 2013)

Classification	Thermal Conductivity, λ, in [W/(mK)]	Thermal Conductivity, λ, in [Btu/(hr ft F)]
"thermally insulating"	≤0.10	≤0.058
"moderately insulating"	0.060 ≤ λ ≤ 0.010	0.035 ≤ λ ≤ 0.006
"well insulating" (typical)	0.030 ≤ λ ≤ 0.060	0.017 ≤ λ ≤ 0.035
"high-performance insulation"	λ ≤ 0.030	λ ≤ 0.017
"super insulation"(nano-porous, normal pressure)	λ ≤ 0.025	λ ≤ 0.014
"vacuum insulation"(silica-based)	λ ≤ 0.008	λ ≤ 0.0046
"vacuum insulation"(high vacuum- based)	λ ≤ 0.002	λ ≤ 0.0012

Source: Data from http://www.schueco.com/web/com

inorganic, synthetic insulation material. Because of its translucent nature and the way light scatters in the material it is nicknamed "frozen smoke"; however, it feels like expanded polystyrene (styrofoam) to the touch. Aerogel is moisture and high-temperature resistant, does not de-color even after long exposure to ultraviolet radiation, and is also highly fire resistant.

From a façade-engineering perspective, the main focus of using aerogel is geared toward its transparent/translucent nature (e.g., designing thermal insulation behind glazing panels that have high-performing insulation and still allow daylight to enter the façades). Currently their practical use is still limited by their relatively high price, despite rising architectural interest for such applications.

One available trade name of aerogel is nano-gel, which consists of 95% air in nano-sized pores that inhibit heat transfer through the aerogel. Made in grades from opaque to translucent, it can be adapted to different environments in conjunction with glazing or other transparent panes such as polycarbonate sheets.

Polyurethane Rigid Foam (PUR) with λ = 0.024 to 0.030 W/(mK) (0.014 to 0.017 Btu/[hr ft F]) This synthetic material is highly insulating and commonly is offered in new sandwich application technologies for structural wall and flooring elements (such as SPS, or sandwich plate system), featuring a polyurethane insulating core and diffusion-resistant metal coatings. These SPS systems are used as façade or roofing elements in the building of cold stores, warehouses, and factory buildings, as well as shipping and transportation containers. Sectional gate elements, doors, and garage doors also are produced with an insulating PUR core.

What makes PUR an attractive choice of material is that in addition to its highly insulative qualities, it can act structurally when used within a sandwich application. These types of systems have been market-ready only as of a few years ago, but they are gaining importance in building envelope designs. However, as currently PUR insulation is still more expensive than other options, it has not yet been able to increase its market share further (see http://www.ie-sps.com for more information).

Pyrogenic Silicic Acid with $\lambda = 0.021$ W/(mK) (0.012 Btu/[hr ft F]) This noncombustible, inorganic, synthetic insulation material is produced by burning silicon tetrachloride in a hydrogen flame, leading to the creation of a microporous insulating material in conjunction with a stabilizer. Further opacifiers, such as titanium oxide, are added to minimize the release of radiant heat. This mixture, together with reinforcing fibers, is compressed under high pressure to form boards with a microporous structure that significantly reduces the migration of gas molecules (heat migration) and hence reduces thermal conductivity down to 0.021 W/(mK).

Despite a very high service temperature range of up to 1050 °C, pyrogenic silicic acid boards only have a small market share (mainly for industrial applications) because of cost. Because of their dimensional stability they are used as the core for vacuum insulation panels (VIP, see section 10.1.4).

Organic Insulation Materials with $\lambda = 0.021$ W/(mK) (0.012 Btu/[hr ft F]) Following recent efforts to limit carbon footprints during manufacturing, organic insulation materials have been investigated with regard to their primary production energy, nonrenewable and renewable resource requirements, and expected life-time durability. With some examples listed in the following, these insulating materials currently hold a small market share percentage and cannot yet be characterized as high-performance insulation. Nevertheless, they stand for a new way of material evaluation based on their overall environmental energy impact and "green feel."

- Wood fibers with $\lambda = 0.040$ W/(mK) (0.023 Btu/[hr ft F])
- Cork board with $\lambda = 0.045$ W/(mK) (0.026 Btu/[hr ft F])
- Cellulose fibers with $\lambda = 0.040$ W/(mK) (0.023 Btu/[hr ft F])
- Hemp with $\lambda = 0.040$ W/(mK) (0.023 Btu/[hr ft F])
- Flax with $\lambda = 0.037$ W/(mK) (0.021 Btu/[hr ft F])

- Reeds with $\lambda = 0.055\,W/(mK)$ (0.032 Btu/[hr ft F])
- Coconut fibers with $\lambda = 0.040\,W/(mK)$ (0.023 Btu/[hr ft F])
- Sea grass with $\lambda = 0.043\,W/(mK)$ (0.025 Btu/[hr ft F])

10.1.4 Vacuum Insulation Panels (VIP)

With conventional insulation materials an increase in thickness is needed to achieve better insulation. However, certain building applications do not allow for multiple inches of insulating layers, which take up more space than what is allocated. Therefore in recent years the idea of applying a thin layer of highly insulating vacuum insulation panels to building envelopes has been investigated. The first application tests of vacuum insulation panels (VIPs) for buildings took place in Germany and Switzerland in 1998/1999. Historically, VIPs had been developed already some time ago for use in appliances such as refrigerators and deep freezers.

In general terms, VIPs are flat elements consisting of an open, porous (and therefore evacuation-capable) core material that has to withstand the external load caused by atmospheric pressure and sustain a sufficiently gas-tight envelope to maintain the required quality of the vacuum (Erb and Symons 2010, Fig. 10-7). Common core materials are fumed and precipitated silica processed within a fleece, open-cell polyurethane and several types of fiberglass. Metalized film, aluminum-foil laminates, or synthetic foils are used to seal the vacuum.

Fibers, open-cell foams, or pyrogenic silicic acid are examples of common filling materials. The initial gas pressure is 1–5 mbar (0.0145–0.0725 psi), depending on the manufacturer, with some minor losses over time, subject to further research and measurements. The gas pressure influences the thermal conductivity. The expected lifetime of the panel is around 30 to 50 years, some claim up to 100 years. Furthermore, VIPs are virtually vapor tight, allowing them to act both as insulator and vapor

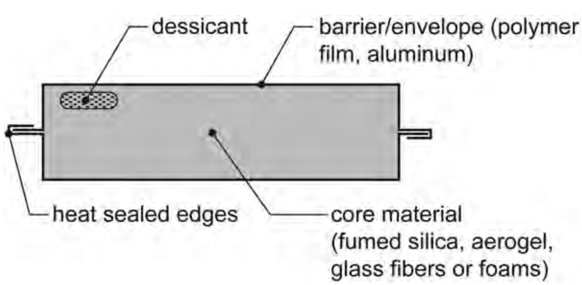

Fig. 10-7. Typical build-up of vacuum insulation panels (VIPs)

barrier, thus preventing the passage of air-laden moisture, a common cause of interstitial condensation.

The panels take advantage of the fact that closed volumes of vacuum are excellent thermal insulators; as a result, their insulation performance is a factor of five to 20 times better than that of conventional insulation. Used in buildings, they enable thin, highly insulating constructions to be realized for walls, roofs, and floors.

The initial thermal conductivity in the center of the panel is as low as 0.0053 W/(mK) (0.0031 Btu/[hr ft F]), increasing to 0.008 W/(mK) (0.0046 Btu/[hr ft F) when accounting for aging and edge losses.

Because of its reduced thickness compared with other highly insulating material layers, VIPs can be used in construction with space constraints, such as balconies or terraces, historic building renovations, and roofing or dormer windows or wall sections, thus maximizing usable floor space and minimizing effects on renovations. A summary image of applications is given in Fig. 10-8.

VIPs are sensitive to mechanical damage and have to be protected before, during, and after installation. Modern infrared (IR) cameras are able to scan the building envelope and find damaged areas, which appear as local energy bridges. VIPs often are installed as a prefabricated sandwich element, where the VIP is combined with other insulation materials,

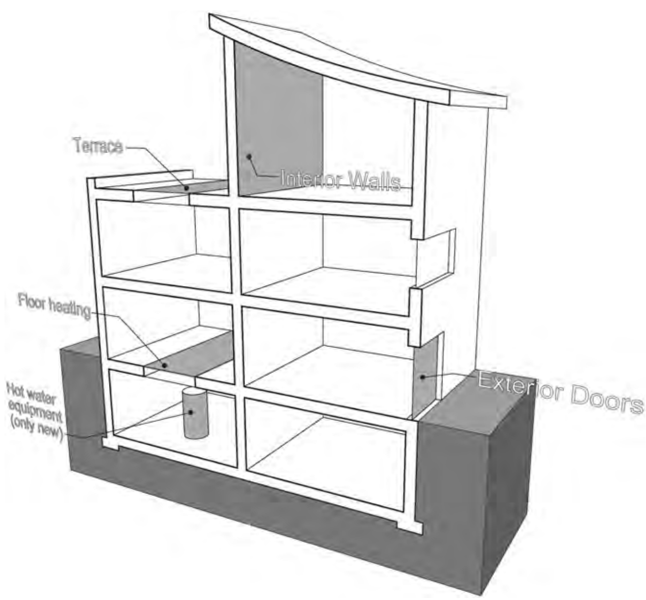

Fig. 10-8. Application areas for VIPs in buildings

such as expanded polystyrene (EPS) or extruded polystyrene foam (XPS). Companies such as Isolar (Isolar Glas. 2013) provide prefabricated VIG panels sandwiched between glass for use in non-vision glazing. These provide structure to the panel while also protecting it from damage. The panels cannot be cut and special sizes are costly; however, less expensive VIP production costs currently are being examined by industry to increase its market share.

Some VIP manufacturers make panels that are characterized by their special film folding technology at the edges, as seen in the va-Q-seam product by va-Q-tec (2013). Therefore, individual panels can be fit tightly together, making an almost gapless assembly possible. After aging and panel-edge loss effects, the panel still achieves a thermal conductivity of only 0.0070 W/(mK) at more than 20 mm thickness and 0.020 W/(mK) if aerated (in case of leakage; see www.va-Q-tec.com for more information).

10.1.5 Vacuum Insulation Glazing (VIG)

Conventional double glazing with a Ug-value of 1.1 W/(m^{2}K) will soon no longer fulfill enhanced governmental energy savings requirements on insulation. Triple glazing does achieve sufficient insulating values (e.g., U ≈ 0.5 to 0.7 W/[m^{2}K] with argon filling and two low-e coatings), but at the cost of increased weight (up to 50%), increased expense, and thicker systems (typically between t = 30 to 50 mm) with reduced visible light transmittance (VLT). A promising alternative to triple glazing is vacuum insulation glass (VIG, Fig. 10-9). In this system, the cavity between the glass panes of a double-glazed unit is evacuated to less than 10^{-3} mbar (0.000145 psi). This almost completely suppresses the thermal conductivity of the gas, which significantly contributes to the total heat transport

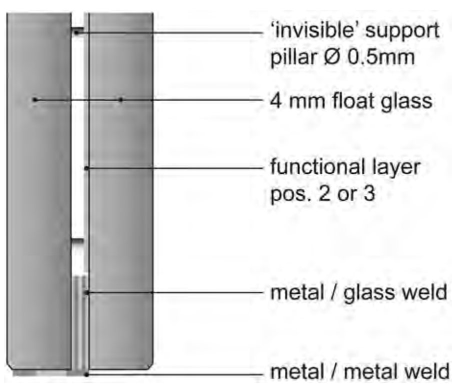

Fig. 10-9. Typical build-up of vacuum insulation glazing (VIG)

in conventional glazing systems (see Bine Informationsdienst 2013 for more information).

The aim of vacuum insulation glazing (also referred to as "evacuated glazing") is to minimize the energy transfer modes of convection and conduction through a transparent window element, reducing energy transfer to the radiation portion alone. The vacuum in between two layers of glazing has a very thin (<1 mm) space evacuated to approximately 10^{-4} torr (1.333 mbar or 0.0193 psi). To keep the vacuum from pulling the layers of glass together, tiny, low-conductivity pillars (stainless steel cylinders, for example) some 30 to 100 mm apart are placed inside the cavity to maintain the spacing between the layers of glass. These pillars are almost invisible during the day and can show up at night to some extent, depending on local lighting conditions.

Current research focuses on increasing the durability of the vacuum-edge seal tightness over time while limiting the heat necessary to create this bond and allowing low-e soft coatings to remain on the inward-facing glass surfaces. For example, sealing metal foils with glass solder, use of complete glass edge joints, and using high barrier adhesives have been examined. The materials used in the edge seal should be vacuum tight and thermally insulating for the duration of the window's service life under all influences and loads. This means that the residual gas pressure of less than 0.001 mbar (0.0000145 psi) in the space between the panes should remain stable for more than 25 years in a temperature range between –40 °C and 60 °C. In addition to the vacuum tightness, providing for a certain amount of elasticity is also necessary. This balances out stresses and thus prevents cracks developing from overstressing the glass edges.

An early method of rigidly bonding the glass panes with glass solder used by some manufacturers cannot fully meet these requirements. VIG production requires temperatures of more than 300 °C, which makes it impossible to use high-quality, low-e soft coatings. These coatings, applied prior to creating the vacuum, cannot withstand high temperatures. The stresses in the edge seals increase proportionately to the size of the glass panes, which can lead to the glass shattering in larger windows and when high temperature differences occur between the inner and outer panes. A potential solution to this problem is using thin metal foil as the edge seal material, where its elasticity balances out the temperature-related stresses. The metal foil is welded ultrasonically to the glass, the resulting chemical bond between the metal and the glass remains permanently vacuum tight. The two panes are then laid together with the spacers between them and laser welded in a vacuum chamber on both sides so that it is gas tight.

With the use of low-e soft solar coatings, VIG reaches insulating values (U) as low as 0.43 to 0.45 W/(m^2K) (center of glass). This performance level aims to convert most windows in heating climates into net energy suppliers, providing more energy to the home via passive solar gain than the window loses in winter time. Current cost and concerns about product reliability due to its minimal use have limited current applications and market share of VIG. However, recent work is focusing on developing the joint and production processes for mass producing VIG systems to be fully market-ready in 2012/2013.

10.1.6 High-Insulating Window Frames

Conventional window frames are often the weak point in otherwise well insulated facades. With a U_{frame} of 1.2 to 1.8 W/(m^{2}K), they have worse insulating properties than standard double-glazed units or high-insulating glazing units such as triple glazed units or VIG with a $U_{glazing}$ of 0.5 to 0.7 W/(m^{2}K). Because both glazing and frame contribute to overall insulation performance, advanced frame systems recently have been developed that achieve U_{frame} = 0.7 W/(m^{2}K) (Table 10-2). The overall U-value for the window as a whole can be determined using the equation shown in Fig. 10-10.

An optimal frame for VIG should cover the thermally bridging edge seal, be slim, and have very good thermal insulation properties. More conventional frames, such as aluminum or PVC, are made through an extrusion processes—methods that also provide little scope for energy optimization. A new framing approach uses cast polyurethane (PU) covered in plastic. The polyurethane foam is poured into a window frame mold to create the solid frame core, which is then covered with a plastic layer that is fully form stable and weatherproof. This polyurethane frame, which also can be fully recycled, has a U_{frame} as low as 0.7 to 0.9 W/(m^{2}K) with a framing depth of only 90 mm.

Research is currently underway in the use of polyurethane technology in the following types of window frames (utilizing traditional frame depths of 120 to 130 mm):

$$U_w = \frac{A_g U_g + A_f U_f + l_g \Psi_g \ (+ \ l_{Inst} \Psi_{Inst})}{A_g + A_f}$$

U_g = U-value of glazing
A_g = Area of glazing
U_f = U-value of frame
A_f = Area of frame
l_g = glass edge length
Ψ_g = thermal bridge coefficient at edge of glass (determined by edge spacer)
Ψ_{Inst} = thermal bridge due to the installation of the window in the exterior wall
l_{Ins} = length where window meets wall

Fig. 10-10. Method for determining U *value of window assembly using EN 10077*

Table 10-2. Overview of Thermal Characteristic Values for Frames and Windows

Window Frame Type	U_f value in [W/(m²K)]	U_w value [W/m²K)] determined for a standard window size 1.23 m × 1.48 m			U_w in [W/(m²K)] taking solar thermal gains into account	
		With double glazing U_g =1.1 W/(m²K)	With triple glazing U_g = 0.7 W/(m²K)	With VIG U_g = 0.5 W/(m²K)	South-facing	North-facing
Standard aluminum window frame	1.8	1.5	—	—	0.49	1.10
Standard PVC window frame	1.4	1.4	—	—	0.39	1.00
Optimized PVC window frame	1.1	—	1.0	—	0.17	0.67
Passive House window frame	0.7 to 0.8	—	approx: 0.8	—	0.00	0.49
New window frame (TopTherm 90)	0.68	—	0.79	.67	–0.15	0.36

- Extruder frame profiles made of PVC with interior steel reinforcement and several air chambers: Additional PU foam elements can further improve the thermal insulation performance of the frame.
- Wooden frame with core insulation or as a sandwich structure with an insulating middle or exterior layer: The insulating material is either PU integral foam, PU recycled material (Purenit), Styrodur, or soft-fiber insulating material; the arrangement of the insulating layers differs among the various manufacturers; wood-aluminum windows also are available with a PU insulation core.
- Aluminum frames where the frame shell is filled with a PU insulation core.
- Other developments include foam-filled plastic profiles, where the steel reinforcement is replaced by profiles strengthened with glass fiber and wooden frames that are combined with externally fitted profiles that are strengthened with wood fibers.

10.1.7 Micro-Lamella/Vector (Patent Pending)

A recent technology that has yet to enter the market and shows promising performance in recent studies is micro-lamella. An example of this technology set to enter the market is called "Vector" by Vitre Glass (Vitre 2013). The innovative idea of this new shading system for glazing in windows is to achieve an angle-dependent shading device that allows clear, unobstructed views within a certain angle of vision but blocks and reflects sunlight entering at more extreme angles, acting like external shading devices. The patented micro-lamella elements are in essence shrink-film louvers that become rigid after production and are fully UV-stable. These micro-thin louvers are embedded within a resin interlayer (approximately 2 mm thick) as part of conventional laminated glazing panels (Fig. 10-11).

Building occupants positioned some distance from the window are able to enjoy an almost fully unobstructed view to the outside. Only when the occupant stands directly behind the window and looks either steeply upward or downward is the view blocked in the same way that solar radiation is blocked. The pending Vector product by Vitre (2013) also aims to offer visual privacy from the outside for higher floor windows, blocking direct views through the windows from the street. This same privacy can be achieved at lower levels with modification of the micro-lamella angle.

In conjunction with solar path and building orientation studies relative to the sun over the course of a year, Vector glazing can reduce solar energy and peak gains from the sun compared with a regular window glazing panel. The new product is expected to enter the market in 2013/2014.

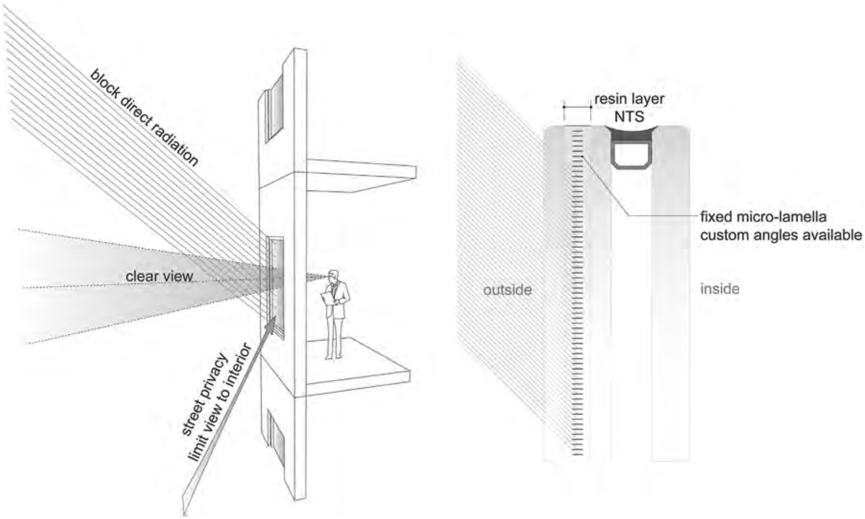

Fig. 10-11. Functionality of Vector product

10.2 HIGH-PERFORMANCE ENVELOPES: ACTIVE SYSTEMS

Active façade systems refer to building envelopes that make use of intelligent window and glazing systems with optical and thermal properties that can change dynamically in response to climate, occupant preferences, and building energy management control system (EMCS) requirements. Active façade systems can be designed to dynamically change the optical and thermal transmission characteristics of windows and the building envelope.

10.2.1 Double Façades

Double skin façades (also known as twin skin façades) have existed for quite some time in various forms. Not until fairly recently have their benefits, pitfalls, and their ability to be fully integrated into the building mechanical systems to best take advantage of their energy-saving potential been fully understood.

The term double skin can imply any number of building envelope strategies that use two layers of façade that work together to achieve a desired effect. A simple rainscreen system can be considered a double skin, because it contains two layers of façade: a primary, internal weather and thermal barrier, and an outer skin used to prevent the passage of most wind-driven rain to the primary skin. However, the double-skin systems that have been the focus of attention and most of the research are those that consist of glazed internal and external skins (at least some percentage of glazing on each). The appeal of these façades lies in the ability to provide a highly effective thermal buffer, while maintaining views and transparency, reducing the passage of noise and odor, and allowing natural ventilation when strong winds are prevalent. Furthermore, these skins are increasingly being tied to the building's mechanical systems to provide added energy savings to the overall system.

These double-skin façades come in a variety of styles, usually customized to the specific project, local climate, and design goals. However, they typically are classified by ventilation strategy, or, simply, how the air in the cavity between the two skins is managed or used. These strategies define the procedure for how the skin operates and responds to local climate conditions. The double-skin systems can be categorized initially by whether its cavity spans a single floor or multiple floors, and then sub-categorized into the following operation strategies (Fig. 10-12).

Fully Sealed Cavity This double-skin system uses a simple strategy of a fully sealed, inoperable outer and inner skin. The skins can be treated in a number of ways to achieve the desired effects on interior building conditions; however, this system is typically best used in heating-dominated climates where a warm cushion is desired around the building to minimize the heating demand. The selection of glazing type on either skin will be based on the desired effects of the system. Although this system is most likely the least costly, it has the potential limitation that the cavity overheats in cooling seasons, increasing the cooling loads. However, this can be mitigated through the use of a mechanical ventilation strategy that exhausts the air when needed or uses the conditioned air within the mechanical system of the building.

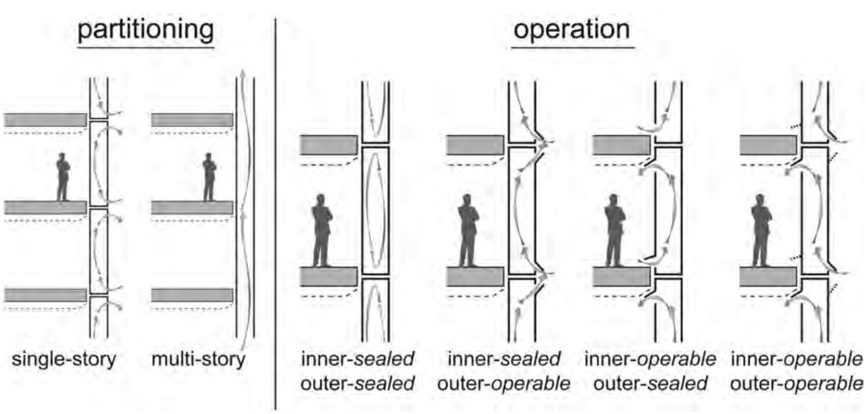

Fig. 10-12. Double-skin façade system types

Sealed Inner Skin; Operable Outer Skin By providing an operable outer skin, the cavity can vent naturally to the outside to moderate the cavity temperature and achieve maximum benefits. This system uses a single-pane glass on the outer skin and insulated glass on the inner skin that acts as the primary thermal barrier.

Operable Inner Skin; Sealed Outer Skin Inverse of the previous scheme, this double-skin system uses an operable inner skin. This system can be designed so that the thermal barrier is on either the inner or the outer skin, the choice of which affects how the cavity may be used. If the outer skin is the primary thermal barrier (insulated glass), then potentially the cavity can be used as an occupiable corridor. Alternatively, if the inner skin is the primary thermal barrier, its operability will allow direct exposure to the conditions of the cavity. However, these conditions are most often best used if integrated with the mechanical systems.

Operable Inner Skin; Operable Outer Skin While arguably the costliest of all options, this system allows for the greatest amount of control. The operability of the outer skin allows direct control of the cavity conditions, whereas the operability of the inner skin allows users or the mechanical system to access the cavity conditions as desired. An additional benefit of this type of system is that the user potentially can benefit from natural ventilation of the interior spaces, a feature hugely beneficial in tall buildings that usually cannot use the high wind speeds for natural ventilation. In the situation where multiple floors or spaces access a single cavity, systems are designed to avoid the cross-contamination of air and odors from one floor to another, as well as the transfer of noise.

10.2.2 Active Coatings/Dynamic Glazing

In an attempt to actively modify solar-energy transmittance, some glazing coating products on the market claim to switch their solar transmittance value on the basis of the active coating approach. The advent of unique films and coatings recently has enabled the industry to offer "smart" glass that can change its chromatic properties based on input conditions or the surrounding environment. The "chromogenic" glazings can be altered actively or passively, effectively transforming their properties based on a number of desired purposes including glare reduction, privacy, daylight and solar control, and reduction of ultraviolet transmission.

Three types of dynamic glazing are quickly gaining in popularity: thermo-chromic films, photo-chromic films, and electro-chromic glass (Fig. 10-13).

Thermo-chromic glass uses a variable tint film applied to the glass as a laminate or within an insulated unit. This film comes slightly tinted and

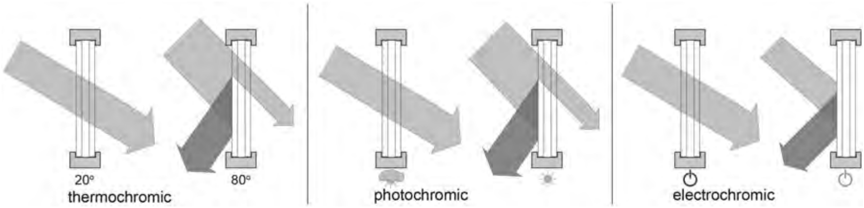

Fig. 10-13. Overview of different switchable optical glazing materials: Photochromic materials become cloudy under bright light, thermo-chromic materials change properties as a function of temperature, and electro-chromic materials respond to an applied voltage (Ander 2004)

Fig. 10-14. Nonactivated (left) versus activated (right) thermo-chromic glass (Pleotint 2013)
Source: Courtesy of Pleotint; reproduced with permission

warms up in the presence of direct sunlight. The warm film darkens, increasing its ability to absorb the sunlight acting on the glass (Fig. 10-14). In combination with a low-e coating, these films can play a large role in reducing the solar heat gain within the building through the fenestration. The low-e coating often is applied to a pane inward of the tint to reflect the heat stored in the film, preventing it from entering indoors via radiation. When not exposed to direct sunlight, the film reverts back to its original tint to allow more of the indirect sunlight into the building.

More commonly found in eyeglass lenses, photo-chromic materials, such as glass or plastic, use chemical compositions that darken when exposed to ultraviolet light and fade back to their initial transparent state when removed from the light. The photo-chromic materials have the capacity to vary their absorption characteristics in response to the radiation wavelengths imposed on it, ultimately affecting the material's transmission levels as well.

In plastics, the photo-chromic additive is a dye consisting of organic molecules that undergo a reversible chemical reaction (darkening) when exposed to ultraviolet light. In glass however, the photo-chromic process is entirely different. Photo-chromic glass uses the light-reactive properties of silver atoms, where the presence and absence of an electron in the atom is triggered by UV radiation, thus triggering the darkening or lightening of the glass. Photo-chromic glass for use in architecture is still in the development stage. Currently the technology works well on small areas of glass, such as in eyeglasses, and has yet to succeed in large-scale applications.

Although intuitively effective for reducing heat gain and glare within buildings, thermo-chromic and photo-chromic glass have a number of drawbacks. Environmentally, these technologies work passively, driven by the surrounding environment. Although this may be beneficial in the summer months, the technology would still block out solar heat that may be beneficial in the winter months. Aesthetically, the user has no control over the appearance of the building. Depending on internal space conditions, more transparency may be desired aesthetically or to achieve desired light levels. Finally, as a result of the sun's direct rays only hitting certain portions of the envelope over the course of the day, the cladding may lose visual consistency.

Electro-chromic glass works in concept identically to the previous types of dynamic glazing, but with the benefit of being control driven as opposed to environmentally driven. Through the application of an electrical charge, the window's optical and thermal properties change from one stage to another (Fig. 10-15). This glass uses a thin, multilayer assembly sputter coated to a laminate glass unit, similar to how low-e glass is created. The two outside layers of this assembly are transparent electronic

Fig. 10-15. Nonactivated (left) versus activated (right) electro-chromic glass (Sage Electronics 2013)
Source: Courtesy of Sage Electrochromics, Inc, © Eric Sahlin Photography; reproduced with permission

conductors. Between these outer layers are a counter-electrode layer and an electro-chromic layer on either side of an ion conductor layer. The introduction of a low voltage across the conductors causes to ions move from the counter-electrode to the electro-chromic layer and results in the the assembly changing color. A return to the original state is done through reversing the voltage and thus moving the ions in the opposite direction.

The benefit of this technology is that the transmissive properties of the glass can be driven through user control or triggered by sensors on the interior or exterior of the façade. Additionally, the glass can be programmed to absorb a specific part of the light spectrum. However, the glass does require electricity to operate, which needs to be taken into account in the building energy demands. Furthermore, the glass can only exist in two states, unlike the constantly variable properties of thermochromic and photo-chromic glass.

Although the authors see a significant potential in active coatings in the future (as they might replace current separate internal and external shading devices on both sides of the glazing), current products do not yet appear to satisfy all architectural needs in terms of their visual appearance given their colored and reflective look. As these systems currently only respond to one parameter (interlayer temperature or electric current), further developments may lead to additional controlling variables such as solar angle incident or preferred amount of visible light, as well as solar heat gain coefficient entering the space.

10.2.3 Phase-Change Materials (PCM)

A phase-change material (PCM) is an active substance with a high heat of fusion, which, by melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage (LHS) units that can be integrated within the building façade as a simple, cost-effective device that can increase comfort and drastically reduce heating demand in cold climates and cooling demand in hot ones.

One well-known phase change material in use is sodium sulfate decahydrate (NaSO4 • H2O, also known as Glauber's salt). Glauber's salt has the convenient property that it melts at 32.4 °C (90 °F) and has about 83 calories per gram. The salt can be stored in black tubes that can be arranged in rows to collect the sun's energy during the day. As the salt absorbs the daytime sun energy, the salt melts. At night as the salt freezes, it releases most of its energy at the phase-change temperature of 32.4 °C (90 °F). A product that uses a similar material called GlassX Crystal by GLASSX (GLASSX®crystal 2013). Glass X Crystal goes one step farther by creating

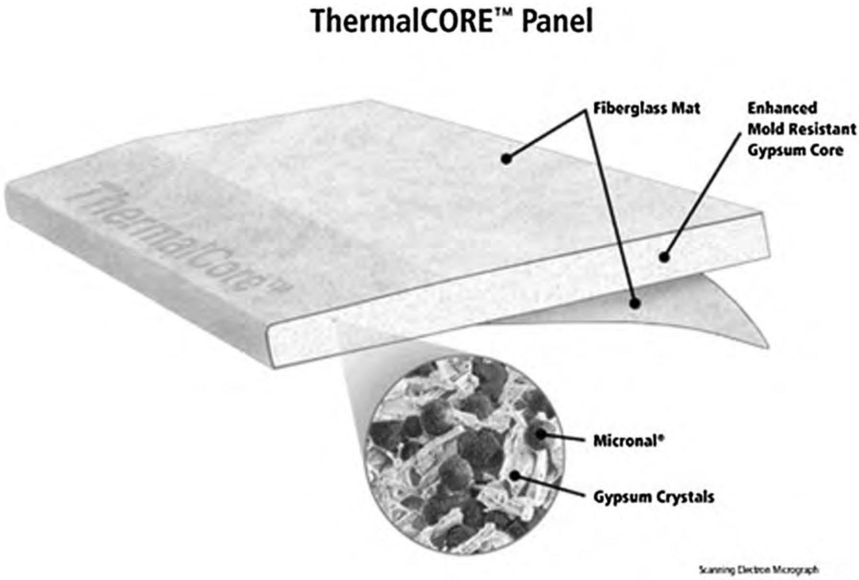

Fig. 10-16. National Gypsum ThermalCore phase-change board with BASF Micronal (ThermalCore 2013)
Source: Courtesy of National Gypsum; reproduced with permission

an all-in-one façade element that incorporates the PCM and integrated shading within an insulated glass unit.

A second example of PCM is Micronal by BASF, in which microscopically small polymer spheres contain a wax storage medium in their cores (ThermalCORE 2013). When incorporated into plasters or gypsum wallboard construction materials, these spherical storage mediums melt and solidify in the microcapsules and regulate environmental temperatures, offering energy savings for cooling and great comfort in the summer by regulating or stabilizing the ambient temperature by capping the temperature peaks (Fig. 10-16).

PCM also can be incorporated into aerated concrete blocks, gypsum plaster, or building blocks and radiant cooling ceiling tiles.

10.2.4 Passive House (German "Passivhaus")

Even though the name suggests a section about passive systems, passive in this case refers to an almost entirely energy-neutral approach to modern construction, including active heat exchange and other active elements that make the Passive House approach part of the active system section.

To reduce overall energy consumption, Passive House is a voluntary standard originating in the German building housing sector to build with a special focus on minimizing energy consumption over the course of a year and lifetime toward a carbon-neutral future (Frey 2011). In essence, a Passive House aims to be a very well insulated, virtually air-tight building that is primarily heated by passive solar gain (due to its correct orientation to the sun) and by internal gains from people, electrical equipment, etc. (Fig. 10-17), For design professionals who are interested in implementing the Passive House, the Passivehaus Institute organization (Passive House Institute 2013) has made commercially available a course and planning material (Passive House Planning Package).

A Passive House is a comprehensive system, where "passive" describes the system's underlying receptivity and retention capacity, while working with natural resources and capturing free solar energy to apply it efficiently. This is in contrast to relying predominantly on active systems to bring a building to "zero" energy. High-performance triple-glazed windows, super insulation, a fully air-tight building shell, limited thermal bridging, and balanced energy recovery ventilation make possible very large reductions in energy use and carbon emission. According to the Passive House standard a building must achieve the following performance characteristics:

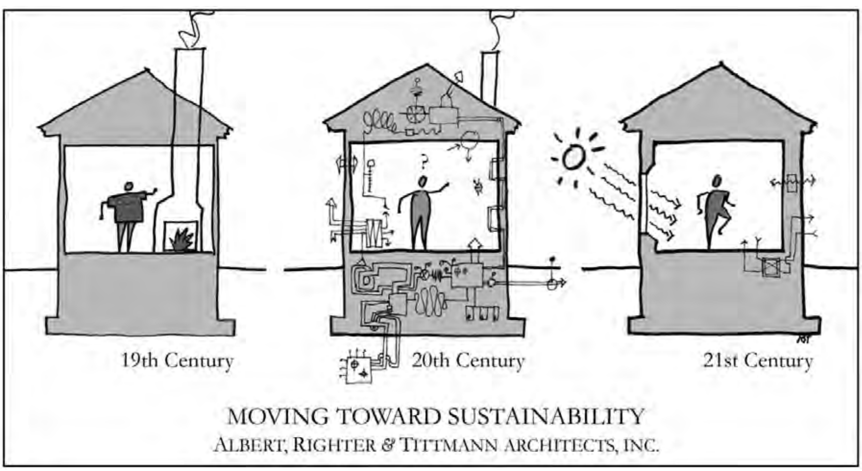

Fig. 10-17. Cartoon comic sketch indicating mechanical-electrical-plumbing (MEP) building complexity (ALRITI 2013)
Source: Courtesy of Albert, Righter & Tittmann Architects; reproduced with permission

- Airtight building shell ≤0.6 ACH @ 50 Pa pressure, measured by blower-door test,
- Annual heat requirement ≤15 kWh/m^2/year (4.75 kBtu/sf/yr), and
- Primary energy ≤120 kWh/m^2/year (38.1 kBtu/sf/yr).

In addition, the following are recommendations that depend on local climate conditions:

- Window u-value U_{window} ≤0.8 W/(m^{2}K),
- Ventilation system utilizing heat recovery with ≥75% efficiency and low electric consumption @ 0.45 Wh/m^3, and
- Thermal bridging-free construction ≤0.01 W/(m^{2}K).

Although the name may suggest that this system applies solely to residential buildings, over the last 10 years more than 15,000 buildings, including schools, factories, and office buildings, have been designed, built, and remodeled to this very progressive standard. While not a curtain wall product, the aggressive approach defined by the Passive House standard often demands innovative products and design approaches to help achieve its requirements.

10.2.5 Building-Integrated Photovoltaics (BIPV)

Solar photovoltaics (PVs) are arrays of cells containing a material that converts solar radiation into direct current (DC) electricity. Materials used for solar cells include amorphous silicon, polycrystalline silicon, microcrystalline silicone, cadmium telluride, and copper indium selenide/sulfide (Jacobson 2009). Historically PVs have been installed on horizontal surfaces such as roofs or open areas of land; however, modern façade design has incorporated PVs into vertical envelope surfaces by means of tilted laminated glass louvers and rainscreen cladding panels. Because PV efficiency depends on location, cloudiness, panel tilt, and efficiency of the panel itself, the application of these systems on the façade may have an effect on the choice and extent of the system used.

For solar PV, the energy payback time generally is longer than that of other renewable energy systems; however, this depends on solar insolation (the measure of solar radiation energy received on a given surface area in a given time) and all the aforementioned factors. The cumulative energy produced from installed solar photovoltaic power at the end of 2009 was more than 20 GW (compared to 8.7 GW at the end of 2007). Despite strong growth, solar power still provides only about 0.5% of global installed electricity capacity. Under the best case scenario in sunny locations, the cost of solar-powered electricity is about USD$0.17 per kilowatt hour (kWh), compared with about USD$0.15 for offshore wind, USD$0.07 for coal and nuclear, and USD$0.06 for gas (not taking into account other factors such as CO_2 footprint, resource abundance, mortality impact, pollution, etc.; Jacobson 2009).

Nevertheless, most likely as a result of various state-provided incentives, recent studies show an increase in PV installations in the United States, a suggestion of the future projection of a much increased PV surface area.

10.2.6 Adaptive Façades ABI/Hoberman Patent

The Adaptive Building Initiative (ABI), founded in 2008, is a joint venture between Hoberman Associates and Buro Happold dedicated to designing a new generation of adaptive buildings (Adaptive Building Initiative 2013). Adaptive buildings optimize their configuration in real time by responding to environmental changes. Whereas adaptive strategies can be applied effectively to a wide range of building systems, ABI is initially focused on adaptive façades and building envelopes. By controlling light levels, solar gain, and thermal performance, ABI's systems reduce energy usage, enhance comfort, and increase the flexibility of the built environment.

Intelligent surfaces—the suite of ABI's adaptive shading and cladding solutions—help connect an occupant to his or her environment in new ways. When a building physically transforms, it in turn transforms the viewer's surroundings through spatial effect or shifting play of light from kinetic surfaces. What these systems have in common are three or more motorized metal screens with translucent patterns or partially fritted glazing patterns that are rotated against each other to vary the amount of daylight transmitted through the system into the building.

The Tessellate system, for example, is a self-contained, framed series of screens whose perforated pattern continually shifts and evolves, creating a dynamic architectural element that regulates light and solar gain, ventilation and airflow, privacy, and views (Fig. 18). Tessellate consists of a series of stacked panels that can be constructed of various metals or plastics. As these layers overlap, the result is a kaleidoscopic visual display of patterns aligning and then diverging into a fine, light-diffusing mesh. Façade benefits are fully variable shading control, reduced solar gain and glare, privacy control, and ventilation and airflow control.

Adaptive fritting is an integrated glass unit with a custom moveable graphic pattern that can modulate its transparency to control transmitted light, solar gain, privacy, and views (Fig. 19). Whereas conventional fritting relies on a fixed pattern, Adaptive fritting can control its transparency and modulate between opaque and transparent states. This performance (possibly as part of an IGU also) is achieved by shifting a series of

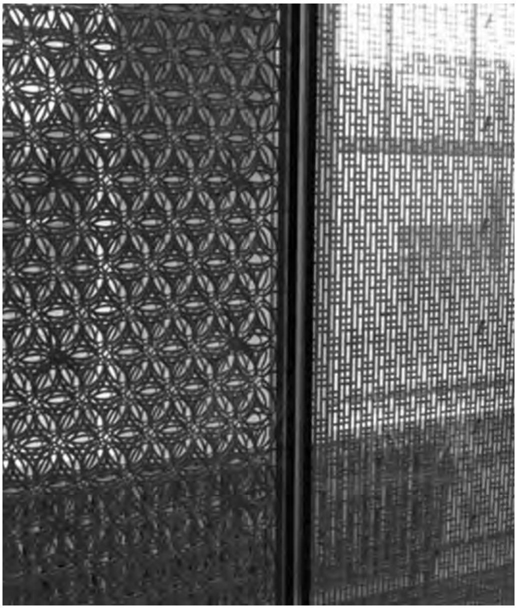

Fig. 10-18. ABI: Example of Tessellate façade panel (Adaptive Building Initiative 2013)
Source: Courtesy of Adaptive Building Initiative; reproduced with permission from Buro Happold

fritted glass layers so that the graphic pattern alternately aligns and diverges.

Strata™ consists of modular units that hide within a single slender profile when retracted. When activated, they extend to form a nearly continuous surface comprising a series of slats that may be constructed of different materials, including metal, plastic, and wood (Fig. 10-20). This system is well suited to applications in which the shading device needs to "disappear" into a building's underlying structure. The advantages of Strata™ include the ability to be designed into nonrectangular shapes, match three-dimensionally curved surfaces when extended, and visually disappear into a building's underlying structure when retracted. Additionally, it can be installed in nonvertical orientations or as a freestanding, structural awning.

10.3 TRANSPARENCY IN THE BUILDING ENVELOPE

The following section describes new trends in transparent curtain wall and building skin design, with transparency of materials being the key driver for views, natural daylight, and architectural expression.

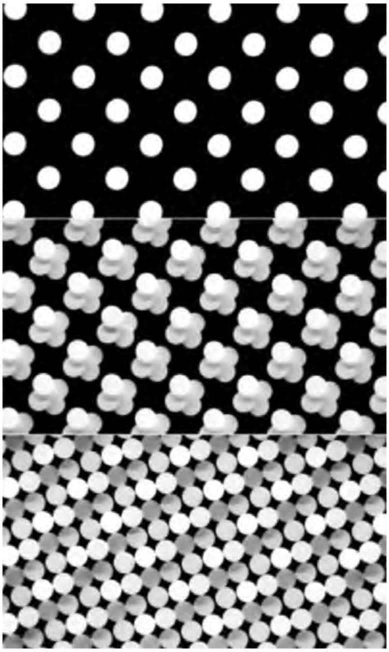

Fig. 10-19. ABI: Example of Adaptive Fritting façade panel (Adaptive Building Initiative 2013)
Source: Courtesy of Adaptive Building Initiative; reproduced with permission from Buro Happold

10.3.1 Load-Carrying Glass/Jumbo-Size Glass

This section will not focus on load-carrying glazing elements, such as laminated beams, columns, or shear-stiffening elements, as they have been known for many years now, just like point-supported, edge-clamped, or drilled bearing glazing connection systems. However, one somewhat new system has entered the market that uses structural sandwich theory for IGU panels, lining together both sides by means of intermediate, rigidly bonded shear frames that are placed in between the glazing next to the air cavity spacers. Together with large-scale autoclaves, safe and super-sized glazing surfaces can be created that no longer need separate substructure glazing mullions or frames but can span long distances that withstand wind and impact lateral loading to code.

For warm-bent curved glazing, the visual quality is often somewhat reduced because of the rollers on which the panels are heated and somewhat distorted during the bending process. To avoid these effects, an improved new cold-bent method has been developed, where glazing panels are cold bent through external force, then laminated and therefore

Fig. 10-20. ABI: Example of Strata façade panel (Adaptive Building Initiative 2013)
Source: Courtesy of Adaptive Building Initiative; reproduced with permission from Buro Happold

superimposed with bending stresses. The end product is a cold-bent single- or multilaminated glazing product that has better visual qualities and a shape with balanced forces due to permanent lamination shear that resists the tendency of the cold-bent glazing panel to revert to its flat state with less internal stresses. Lamination is achieved by means of the vacuum-bag method. The glazing industry continuously is pushing the maximum sizes of glass products that can be produced. Seele Sedak GmbH & Co, a leader in the field of high-quality and oversized glass, currently offers max jumbo sizes as shown in Table 10-3.

10.3.2 ETFE Foil

Originally developed as a wrapping foil material for the packaging industry, ETFE foil (ethylene tetrafluoroethylene) is a water-tight fluorine-based plastic that can be applied to buildings as either a single-layer foil or as a pneumatic double- or multilayer cushion with active internal

Table 10-3. Example of Available Glazing Sizes (Sedak 2013)

Glass cutting:	3.30 m × 16.00 m; 10′ – 9″ × 52′ – 6″
Glass machining:	3.21 to 3.60 m × 16.00 m; 10′ – 6″ to 11′ – 9″ × 52′ – 6″
Machining methods:	drilling, milling, edgework = seamed, grounded, polished, or high-gloss polished
Glass lamination with vacuum bag:	Autoclave 1: max. 4.00 m × 17.00 m; 13′ – 0″ × 55′ – 9″
(with lamination interlayer types being SGP/PVB/TPU/EVA and others)	Autoclave 2: max. 3.28 m × 15.00 m; 10′ – 9″ × 49′ – 2″
With intermediate layer options being:	Autoclave 3: max. 2.80 m × 12.50 m; 9′ – 2″ × 41′ – 0″
SEFAR Fabrics/Southwall XIR-Interlayers and others	Autoclave 4: max. 0.60 m × 1.50 m; 1′ – 11″ × 4′ – 11″
Heat-treated glass (fully tempered or heat strengthened):	Min. 200 × 600 mm up to max. 3.21 m × 15.00 m; 8″ × 24″ up to 10′ – 6″ × 49′ – 2″
Fully tempered:	6 mm – 19 mm; 1/4″ – 3/4″ glass thickness
Heat strengthened:	6 mm – 12 mm; 1/4″ – 1/2″ glass thickness
Heat soak test:	3210 × 15000 mm: 6 mm – 19 mm; 1/4″ – 3/4″ glass thickness
Bent heat-treated glass:	Min. 400 × 600 mm up to max. 3.21 m × 5.00 m; 10′ – 6″ × 16′ – 4″
Heat treated: 6 mm – 19 mm glass thickness	Min. bending angle: 90°
Min. bending radius:	1500 mm; 5′ – 11″ (glass 6 and 8 mm; 1/4″ – 5/16″) 2000 mm (glass 10 and 12 mm; 3/8″ – 1/2″) 2500 mm (glass 15 mm; 9/16″) 3000 mm (glass 19 mm; 3/4″)
Lamination "cold"-bending:	Maximum dimensions: 3.21 m × 15.00 m; 10′– 6″ × 49′ – 2″
Note: the minimum cold-bending radius is, as a rule of thumb (and depending on other load stresses on and within the glass unit) approx. 1,500 times the thickness of the thickest glass sheet in the lamination buildup (e.g., a glass unit out of 10 mm glass sheets has an approximate bending radius of 15 m on the average)—the actual structural calculation may result in a slightly smaller or larger radius.	

Source: Data from Seele Sedak GmbH & Co; www.sedak.com.

positive air pressure to achieve its synclastic shape. ETFE's material properties according to (Lehnert and Schween 2010) are as follows:

- Tensile strength >50 N/mm² (7.25 ksi),
- Elongation at break >350% according to DIN EN ISO 527-1 (ISO 2012),
- Tearing resistance >400 N/mm (2284 lb/in.) according to DIN 53363 (DIN 2003),
- Cold temperature resistance of –160 °C,
- High light transmission including UV radiation,
- UV stable and aging/weathering resistant,
- Anti-adhesive smooth surface (self-cleaning),
- Resistant to hail according to Swiss Engineering and Architect Association (SIA) document SIA V280 (SIA 2013) and the European Standard BS EN 13583:2012 (BS EN 2012).
- Young's Modulus of approximately 700 N/mm^2 (101 ksi),
- Fire class B1, nonburning drip from 250 °C (482 °F),
- Suitable for welding, and
- Fully recyclable.

Because of the ability to weld ETFE roll width bands into wider pieces, large bays of ETFE cushions can span in between secondary framing, allowing for long-span façade segments that also can be twisted to create irregular geometries. This is possible because the sheet or cushion can be patterned correctly prior to tensioning or inflation to allow its final form to match the desired surface geometry. Rolls of foil, ranging from 100 μm to 250 μm thickness, are cut to the desired shape and are welded together to form cushions.

The pneumatic pretensioning with a low-pressure air system gives the cushions a stable shape and prevents the foils from billowing and fluttering in wind conditions. The cushions are fixed by means of a continuous "keder" (beading) piping connected to a lightweight extrusion. The extrusion is bolted to the supporting structure to provide a frame onto which the cushion is mounted. The following are some advantages of ETFE cladding over glazing systems:

- The system has low ETFE weight (particularly advantageous for refurbishment projects and light-weight structures).
- Possibility of wider spans result in larger transparent/translucent spaces.
- Flexible 3D shaping (free-forms through cutting pattern) are available.
- The system is suitable for cable structures because large deformations are not critical.
- A large range of coloring and graphic printing is available.

- Lower cleaning costs (depending on type of application) is possible.
- The system has excellent UV transmission.

The high rate of UV light transmission can be beneficial and a decisive choice in enclosures for greenhouses, botanical gardens, swimming pools, and stadium roofs with grass pitches. The material does come with some shortcomings, including the following:

- Maintenance of the inflation unit is necessary for the active pressure system (about 200 Pa internally) and operating cost.
- The system has poor acoustic insulation (yet good spatial acoustics with short reverberation times).
- There is less clear transparency/visual appearance compared with glazing panels.
- There is less effective thermal insulation compared to IGU (2.94 W/m^2K for a two-layered ETFE cushion, which can be reduced with further intermediate layers).
- It is necessary to avoid ponding caused by rain or melting snow or cushion malfunctions.
- Internal cushion pressure creates permanent horizontal support forces that need to be anchored.
- The curvature requirement of the cushions do not allow for flat architectural surface expressions; single foil systems have no bending stiffness and hence need to be limited in span (catenary structural action).

A recent development includes the integration of photovoltaic cells into ETFE cushions, allowing solar energy to be collected. For example, Texlon solar cells are made in a continuous roll deposition process and laminated into the upper foils of Texlon cushions. Bypass diodes are connected across each cell, allowing the modules to produce continuous power even when partially shaded. Each cell is composed of three stacked semiconductor junctions. The bottom cell absorbs red light, the middle cell green light, and the top cell blue light. Texlon's high light transmission coupled with the cells spectrum-splitting capability aims to ensure enhanced efficiency (Lehnert and Schween 2010).

10.3.3 Polycarbonate Panels

As a transparent or translucent alternative to glazing panels, polycarbonate (PC) has entered the façade market in the form of flat or corrugated sheets, ranging from clear to translucent and tinted in color, with single or multiwall assemblies (trademark names include Lexan, Makrolon, Macroclear, and others). This particular group of thermoplastic polymers is easily worked, molded, and thermoformed for façade and roofing applications. Its high strength compared with its light weight allows for shatter resistance in bullet-proof and bomb blast applications and can even be welded, resulting in invisible joints to achieve large panel sizes. Polycarbonate panels have a density of 1.2 g/cm^3 compared with glazing with 2.5 g/cm^3, their stress values at yield are approximately 60 MPa for tensile (50 mm/min) and 90 MPa for bending (2 mm/min), with a Poisson ratio in the order of 0.38 (compared to 0.23 for glazing) (Lexan 9030 datasheet).

PC panels have found their applications in the contemporary façade marketplace, in part because of their long-term scratch resistance and overall flexibility compared to glazing, given its modulus of elasticity, which is in the range of E_{PC} = 2,300 MPa (compared to E_{glass} = 70,000 MPa) (Lexan 9030 datasheet).

10.4 DIGITAL DESIGN, ENGINEERING, AND FABRICATION

"Geometry follows form." The design of specialty structures or building envelopes typically requires the integration of structure, form, façade, sustainability, and materiality into one single interdisciplinary design approach. When the architectural vision includes nonplanar transparent freeform surfaces, a detailed geometric analysis typically becomes a required part of the early design phase. Not only can it result in alteration requirements affecting the form or selected structural systems, but it can be leveraged as a comprehensive framework from analysis and design to digitally controlled fabrication.

Although free-form façade geometries always can be clad in triangles, their higher cost and frequently visually obstructive diagonals make designers prefer envelopes based on quadrangles, with the challenge to create curved surfaces out of a series of flat trapezoidal elements.

From an international point of view, recent research in the field of engineered glazing systems is expanding beyond aspects of load-carrying capacity or the development of new fixing systems (such as glued bondings or new types of fasteners) toward a more integrated approach to the interaction of glazing systems and geometric surface form, triggered by the increasingly free-form façade designs in recent architecture, which ultimately have to be converted into realistic, cost-efficient, structurally stable, and safe built constructs.

Unlike the past, when curved surfaces were either panelized by means of warm-bent glazing or facetted subdivisions in which four-sided glazing remained in a single plane (flat after installation), today 3D-software tools allow a more flexible approach with improved geometric form flexibility, in which "stepping" or "twisting" (so-called cold-bending) of glazing panels can be used. Given that all technical detailing boundary conditions are properly understood (such as the requirement of long-term water and air tightness of the nonplanar curtain-wall systems), high-performing glass enclosures can be designed and detailed within the digital environment to assure their feasibility.

10.4.1 Cold-Bent Glazing Approach

With architectural shapes of building envelopes that no longer follow rectangular flat surface layouts, façade engineering needs to respond to free-form surfaces that allow panelization while simultaneously maintaining cost-efficient approaches. Rather than subdividing such surfaces into triangles, cost-efficiency might be achieved by taking flat trapezoidal quadrangles that are slightly cold bent into a 3D-shape, hence avoiding the extra cost of triangular-shaped glass cutting, increased framing, or warm-bent molding (Fig. 10-21).

This somewhat new technology finds its limits not necessarily in the limitations of the glass, but in a potential loss of primary sealant performance of the sealing butyl between the glass panels and the spacer material, if bent or twisted too much (Fig. 10-22). One possible relevant reference length useful in the design stages might be the average diagonal $D_{ave} = (D_1 + D_2)/2$ with the maximum allowable twist (corner offset distance to plane created by the remaining three corners) set to $D_{ave}/175$.

10.4.2 Parametric Façade Design

Modern software tools such as Grasshopper (parametric add-on software for Rhino) allow the designer to set the initial parametric variables

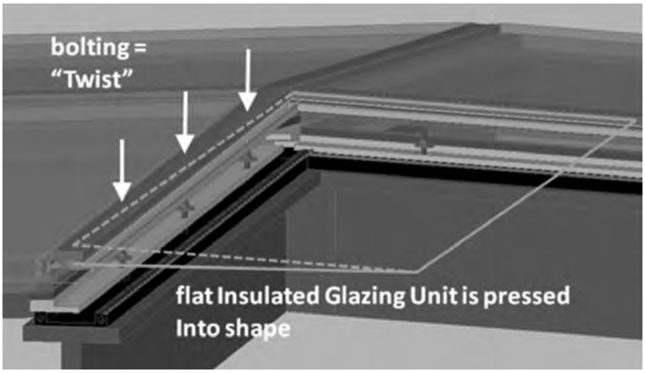

Fig. 10-21. Example of cold-bent glazing panel, twisted into shape by means of bolting

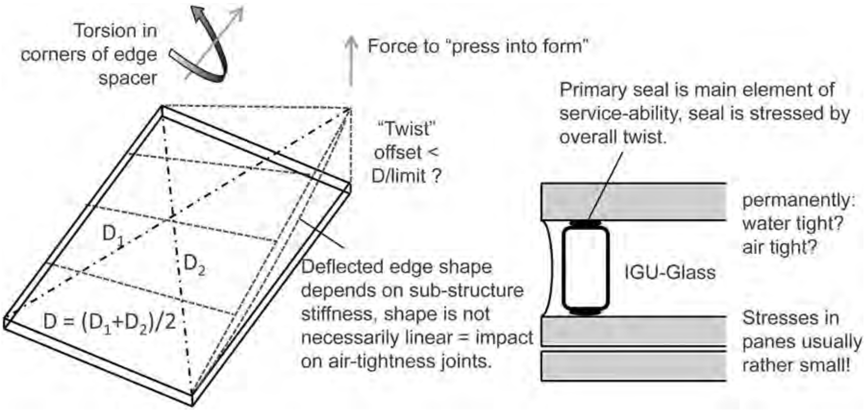

Fig. 10-22. Serviceability limits of IGU due to cold bending
Source: Laufs and Vilkner (2010)

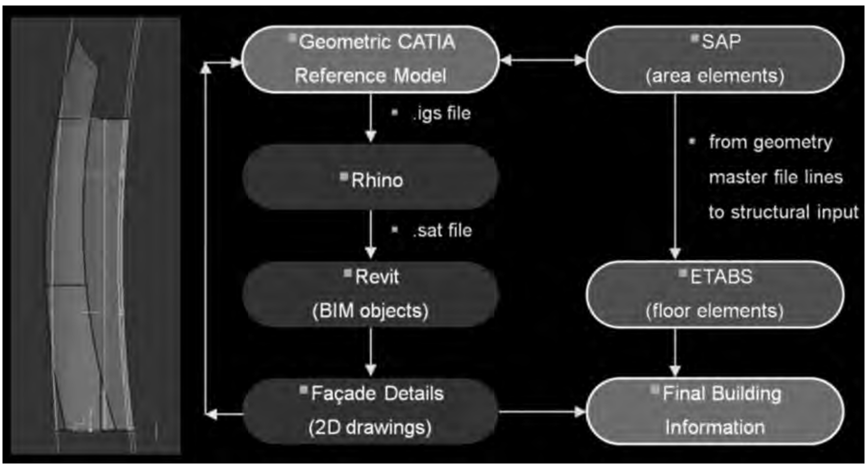

Fig. 10-23. Example of data down-streaming from parametric, master model geometry
Source: Laufs and Vilkner (2010)

driving the geometry and allow for adjustments that trigger automated updates of sections and details, hence, saving time when fundamental design changes would otherwise require a chain of manual updates for related drawings. Among other benefits in the design process, these software tools (Fig. 10-23) are a means to capture, create, assess, and output fabrication details and components accurately in a visually rich 3D environment.

On a design level, certain irregular shapes, such as panel sizes, limiting angles, or other curtain-wall–related boundary conditions, can be queried and highlighted with the use of parametric design tools. One example is to find suitable subdivision joints for curved curtain wall surfaces that allow façades to be based on flat quadrangles with initial gridline spacing needs to be determined. Some possible geometry approaches are "identical divide," "equal spacing," "translation," "master-slave-curves," and superposition of such techniques (Laufs and Vilkner 2008).

For complex building envelopes, the initial extra time spent at the early stages to set up a parametric model is usually a worthwhile investment that allows later control over complex geometries. While parametric design does not replace the quality of thoughtful architectural design, it can be linked directly to manufacturing and hence increase efficiency.

10.4.3 Digital Fabrication and Interoperability—BIM

To efficiently execute analysis and design of innovative façades with challenging forms, not only is using modern 3-D software tools essential, but so are understanding and leveraging how models in different software environments can be integrated with various interoperability techniques (Laufs and Vilkner 2010).

In the context of building information modeling (BIM), such an approach allows understanding of specialty building envelopes as complex data structures rather than as a sequence of design drawings. In the early design stages, using interoperability techniques allows superior coordination and visualization and the creation of a precise bill of materials and complete listings of geometric conditions. In later design phases, it enables prototype generation in various scales and automatic generation of shop documentation and machine-readable files.

A holistic interdisciplinary design approach to specialty building skins further includes diverse aspects such as lighting, transparency, energy balance, cleaning, and management of rain water strategies, to name a few. All these are design aspects to address early that directly affect any geometric reference model. The inherent challenge that comes from integrated design methodologies is that design changes become difficult. It is therefore important to consider automation strategies in all stages and processes that typically would require extensive manual efforts to be redone with slight changes and adjustments. The design of specialty structures or building envelopes typically requires the integration of structure, form, façade, sustainability, and materiality into one single interdisciplinary design approach. When the architectural vision includes nonplanar transparent freeform surfaces, a detailed geometric analysis typically becomes a required part of the early design phase. Not only can it result in alteration requirements affecting the form or selected structural

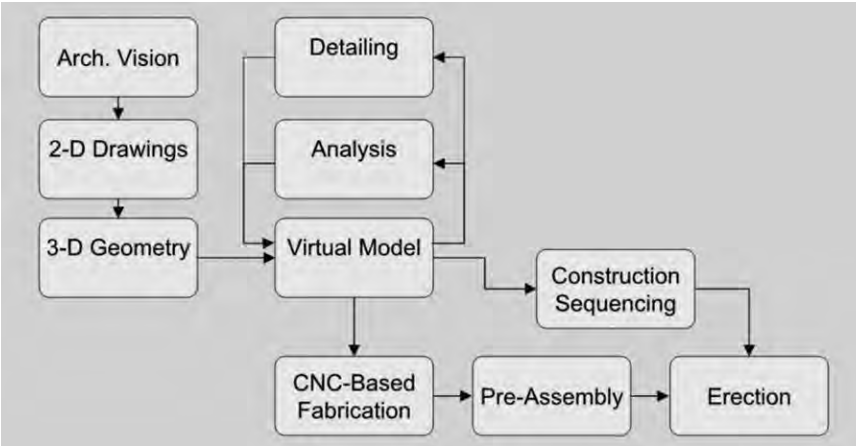

Fig. 10-24. Integrated design including geometry, details, calculation, and manufacturing (Adaptive Building Initiative 2013)
Source: Courtesy of Adaptive Building Initiative; reproduced with permission from Buro Happold

systems, but it can be leveraged as a comprehensive framework from analysis and design to digitally controlled fabrication. Current industry standards used in the design of building enclosures include NURBS modeling software such as Rhino, CATIA/Digital Project, Generative Components, SolidWorks, and Autodesk Inventor.

The elements created in such tools are used as geometric reference models that control the detailing for the skin objects and the precise geometric boundary conditions for the structural support systems. To efficiently execute analysis and design of specialty structures with challenging forms, not only is using modern 3D software tools essential but so are understanding and leveraging how models in different software environments can be integrated using various interoperability techniques. It is the opinion of the authors that current processes for designing integrated, high-performance façades with nonstandard geometries require the use of a fully integrated, parametric approach to achieve greater precision, understand and rationalize complex façade shapes early on, allow for optimization and repetition, and hand over digital data with cost advantages through the fabrication stage (Fig. 10-24).

10.5 SUMMARY AND OUTLOOK

This chapter offers a brief overview of façade innovations as seen from the perspective of façade engineering consultants inspired by recent requirements for energy-saving and energy-producing buildings and new material technologies in tandem with a more active understanding of temperature and ventilation management. These innovations should also be considered by means of adapting BIM-related tools that focus on unity of the design process: linking data all the way from the early building envelope design sketch to the manufacturing floor. By facing daring artistic skin visions with thoughtful detailing, excellent geometric control, extensive analysis and design, outstanding and innovative building envelope systems can continue to be realized.

So what's next? What is to come in the near future? Anything new under the sun? Beyond better coatings and further improved performance values of façade products, an adaptation of existing sensor technology in conjunction with intelligent climate control of the building envelope is likely to occur. A windy rainstorm will cause the façade to adapt differently than it would on a hot sunny summer day, yet not so much by expensive motorized active louver systems but more by integrated, adaptive (glazing) screen, based on existing TV and future nano-technology, made market ready for mass production. Like the responsive human skin or the adaptive skin of a colorful octopus to its current underwater environment, this will likely also affect architectural façade appearance, which can be programmed in color, tectonic quality, surface roughness, and thermal performance with exciting new possibilities to come for the world of curtain wall enclosures.

In this context, curtain wall research needs to shift and open up into areas beyond its more classic roots in the fields of civil engineering and architecture. Future venues of façade innovation will be found in the fields of nano-technology/biochemistry, adaptivity (biology/bionics), and computer sciences (information technology software development and application). Façade design will be able to benefit from other research fields and transfer relevant trends and applications into the building envelope of tomorrow.

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CHAPTER 11

NEW DEVELOPMENTS IN CURTAIN WALL AND GLAZING SYSTEMS

Ali M. Memari

Today, higher demand exists for high-performance buildings in general and for curtain wall systems in particular. The expectations of the glazing systems are very high; as a result, creating an envelope component that provides vision, daylighting, ventilation, and protection from environmental and variable climate effects is insufficient. The curtain wall system is now considered one of the most important components in buildings that can help save heating, cooling, and lighting energy and, in some cases, even generate electricity.

Advancements in glazing system design include tinted glass, various coating types on glass or film surfaces to address different needs for solar heat gain coefficient (SHGC), insulation (u-value), visual transmissibility (T_v), addition of various types of insulation between glass panes in multipane glazing, use of polycarbonate-based glazing as an alternative to glass, incorporation of vacuum glazing, creating ventilation between glass panels as in double-skin façade, and incorporation of photovoltaic on glazing, to name a few (Memari and Ariosto 2011). According to Mignat (2007, p 54), "curtain wall construction has developed into a key technology that can improve the energy efficiency of a building and turn buildings into power plants for energy generation."

This chapter introduces several more recent technologies developed to address the desired energy efficiency of glazing systems and also to discuss some glazing systems that require advanced structural analysis for their design (e.g., point-supported glass). Some of the discussions in this chapter complement the material presented in Chapter 10.

11.1 ATTACHMENT OF GLASS PANES TO FRAMING

The aesthetically pleasing all glass and transparent curtain wall without exposed framing has been a strong incentive for glazing system designers to develop new technologies for attaching glass edges to the framing system and for reducing the size of the supporting system (GANA 2005). Prior to the development of more modern glazing and sealant materials, putty was the most commonly used material to attach the glass to the framing and provide a seal and to transfer loads from the glass to the framing. As putty dries over time, it loses the flexibility needed to accommodate thermal and wind or seismic related in-plane movements, with the result of leaving the glass more vulnerable to breakage. The next generation of materials used to substitute putty included rubber gaskets holding the glass edges within the framing pockets (Memari et al. 2003) and more recently structural sealant such as silicone, i.e., structural sealant glazing (Memari et al. 2006, 2011a). Both rubber gaskets in dry-glazed systems and structural sealants hold the glass edges to the framing continuously like putty. While rubber gaskets rely on the force from pressure plates fastened to the framing with screws to provide sealant function, structural sealants do not need external pressure to hold the glass in place and can provide sealant function, much like putty, but retain their flexibility over the years. Structural glazing tapes also have been introduced to attach glass panes to the framing (Memari et al. 2011b) just like structural silicone. In one development with a drastic departure from continuously supporting the glass edge, point-supported glass has evolved as described in the next section, where glass pane is fastened to the supporting system mostly at corners.

11.2 POINT-SUPPORTED GLASS SYSTEMS

In point-supported glass (PSG) the glass pane is attached to the supporting system using bolt fittings through predrilled holes in the glass. The biggest challenge in design of PSG systems is to avoid cracking in glass under various types of loads expected to be experienced by the glass while interacting with the supporting system through bolts. In fact, because of the sophistication of the stress states in glass at connection points, no standard exists for design of such systems and much reliance is placed on the experience and expertise of the design professional to use advanced analysis tools to investigate stress states around the holes (e.g., Stutzki et al. 2004). Design of glazing with continuous glass edge attachment to the framing (e.g., dry glazed or structural sealant glazing) is covered by ASTM Standard E 1300, "Standard Practice for Determining Load Resistance of Glass in Buildings," (ASTM 2009). Furthermore, depending on the size of the glass lites, out-of-plane deflection of the glass could actually govern the design because with no continuous edge supports and use of thinner glass lites, glass deflection will be larger under wind load (GANA 2005). For this reason, advanced structural analysis tools such as finite element modeling (Vyzantiadou and Avdelas 2004) generally are used to ensure the stresses in glass do not approach critical levels and deflections remain within acceptable range. Other methods of analysis include rapid prototyping technology combined with stress photography (Knowles 2003, McGeen 2004).

The supporting systems for PSG can take various truss-work shapes and forms, including a combination of cables, rods, and glass plates. The bolt fittings holding the glass pane corners are attached to the supporting systems through various hardware and mechanisms such as four-pronged stainless steel fittings or "spider" fittings. The connection hardware is in turn attached to the supporting system through cables or rods. Fig. 11-1 shows a building with glass held in place using PSG system, while Fig. 11-2 shows how the spider fittings attach the exterior glass panes to the interior glass fin.

The glass panes can be either completely separated (at the edges) from each other in some curtain wall designs if air and water sealing is not required or silicone sealant can be used to attach adjacent glass pane edges to each other. PSG system can be used in vertical and sloped glazing (Sakula et al. 2001, Post 2000, Dawson 2000). Although for vertical glazing any type of glass (annealed, heat strengthened, or fully tempered) and configuration (monolithic, laminated, or insulating glass unit

Fig. 11-1. Example of point-supported glass system on a building

Fig. 11-2. Spider fitting attaching adjacent glass pane to the glass fin

configurations) can be used; for sloped glazing and overhead canopies, because of the long-term gravity loads and perhaps additional load from snow (GANA 2005), heat-strengthened laminated glass should be used to reduce life-safety consequences in case of failure.

11.3 DOUBLE-SKIN FAÇADE

Double-skin façade allows shading and ventilation to be incorporated as well as insulation with a wide separation between interior and exterior glazing. According to Boake (2003), the air space in the cavity provides a buffer to control thermal, wind pressure, and sound effects. It further provides a medium for incorporation of shading devices. The overall objective of double-skin façade design is improvement in energy performance and occupant comfort through natural air ventilation (instead of mechanical air conditioning), shading, daylighting, and passive solar gain with the use of spectrally selective glazing (Boake 2003).

The use of large glass panes allows more natural light and can reduce lighting energy. According to Mignat (2007, p 56), "The requirement for artificial light can be reduced by 60 to 70 percent. With improved utilization of solar radiation and solar heat, the heating requirement decreases by 40 to 60 percent, and the cooling loads and air-exchange rate can be reduced by 70 to 80 percent." Although such estimated energy savings are for European climates, the reduction in cooling loads in hot arid climates could be between 19 to 40% depending on the exterior glazing properties (u-value, SHGC, and T_v) according to Hamza and Underwood (2005). Some architectural and structural design aspects of double-skin façade in addition to the building physics issues are discussed by Tenhunen et al. (2002). Several comprehensive research projects have been carried out on double-skin façade as reflected in the following documents: Boake et al. (2008), Arons (2000), Yellamraju (2004), Poirazis (2004), and Gratia and Herde (2007). Aside from the studies related to design properties and energy performance of double-skin façade, one study (Moon 2009) discusses a structural damping effect of this exterior skin system on control of tall building motion.

11.4 BUILDING-INTEGRATED PHOTOVOLTAIC (BIPV) GLAZING

Harvesting solar energy to generate electricity (photovoltaic) or heat water or building interiors (solar heat gain) is now an accepted approach as a renewable form of energy. Because conventional photovoltaic (PV) array systems have been designed as roof-mount systems (Figs. 11-3 and 11-4), they are not normally suitable for wall systems. Furthermore, from aesthetic and architectural points of view, mounting conventional PV arrays on walls is not desirable. A new approach has been developing to integrate PV modules into building envelope materials and components such that a PV system is not an added component but rather a part of essential building envelope materials. This concept, known as building-integrated photovoltaic (BIPV), has encouraged PV manufacturers and

Fig. 11-3. Use of roof-mount solar arrays on Solar Decathlon House at Penn State University

Fig. 11-4. Roof-mount solar arrays and support framing on a house in Los Altos Hills, CA (view from hilltop, solar panels facing downhill)

Fig. 11-5. Use of wall-mount (sidings) solar arrays on Solar Decathlon House at Penn State University

building product developers to think of innovative ways to incorporate PV into building envelope components (Benemann et al. 2001, Strong 2010, SEI 2004, SDA 1997, Sick and Erge 1996, and Riffert et al. 2000).

Examples of BIPV technologies include PV-integrated shingles or sidings as shown in Fig. 11-5 (e.g., Atlantis Energy Systems [Sunslate], SunPower Corp. [Suntiles], and BP Solar); PV-integrated metal roofs (e.g., UniSolar [EnergyPeak] and SunTech [JustRoof]); metal panels used as curtain walls (Yoshino et al. 1994); and PV-integrated glazing (e.g., MSK Solar Buildings and Schatt).

The electricity generated by the BIPV system can be stored in batteries so that the system can be used as an off-grid system. Alternatively, the system can be interfaced with the utility grid and the electricity generated sold back to the grid. Of the main two basic types of PV module technologies, crystalline silicon cells are capable of producing 10–12 W/ft^2 of PV array, while thin-film materials may deliver 4–5 W/ft^2 of PV area according to Strong (2001).

Both types of PV modules (thin-film and crystalline silicon cells) have now been incorporated into different glass configurations such as laminated glass and insulating glass units (IGU). Fig. 11-6 shows an example of the use of crystalline cells within the interlayer of a laminated glass configuration and a drawing showing the layers in such a configuration. In general, crystalline cells are opaque and must be spaced over the glass surface to allow some light to go through and therefore result in a glazing with lower visual transmissibility (T_v) compared with thin-film-type PV. Depending on the level of daylighting desired, the opaque crystalline modules can be spaced to provide the needed daylighting level. According to Strong (2001), a laser-etching process can be used with thin-film modules to allow light transmission through desired patterns for overhead glazing applications. Besides application for vision areas, BIPV also can be used for spandrel (nonvision) areas of curtain walls. Ishikawa et al. (1996) have developed BIPV glazing using color solar cells to provide architects with a variety of design options.

For IGU configurations, usually the outer pane will have the PV module integrated into it. One issue that needs to be considered is whether IGU can provide sufficient ventilation for the PV module to reduce heat buildup within the cavity. Fung and Yang (2008) have studied the thermal performance of BIPV glazing systems that are semitransparent. In

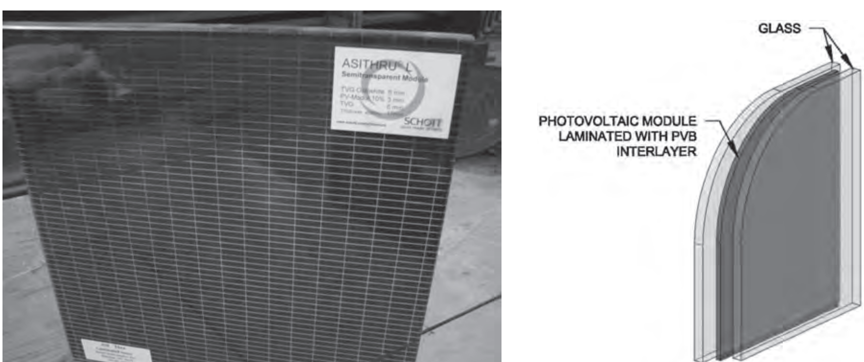

Fig. 11-6. Photo showing sample of laminated glass with crystalline cells within the laminate and a drawing showing the layers

particular, they have evaluated the reduction of solar heat gain (SHG) owing to the use of opaque PV modules within insulating glass units. In such designs, as the spacing between opaque solar modules integrated on the glass surface is reduced, although more electricity can be generated and SHG reduced, the daylighting is also reduced. According to Fung and Yang (2008), a balance should be created among the three aspects of power generation from solar modules, SHG, and the desired daylighting (T_v).

11.5 LOW-E COATINGS AND TRANSPARENT/TRANSLUCENT INSULATION

One efficient way to increase the insulation property (reduce u-value) is by suppressing radiation heat flow through application of a low-e (low-emissivity) coating on the glass surface. The coating material varies depending on the performance objective required of the glazing. In general, the basic coating consists of depositing metallic oxide layers through different techniques. Spectrally selective glazing (PPG Industries) uses coatings to control the amount of different portions of the solar spectrum that can go through the glazing. Fig. 11-7 shows samples of spectrally selective insulating glass units. The objective is to allow desirable amounts of daylighting (visible solar wave radiation) to go through while rejecting the transmission of long-wave (infrared) and short-wave (ultraviolet) solar radiation (FTA 1998). As an alternative to spectrally selective low-e coating that consists of microscopically thin silver-based multilayer low-emissivity coating on the glass surface, tinted glass also can perform some of the functions of the low-e glass. The basic difference is that in tinted glass the impurities within the glass absorb portions of the solar spectrum and prevent their transmission to the interior, whereas the low-e coating reflects most of the short- and long-wave solar radiation. However, according to FTA (1998), because some of the absorbed heat in the tinted

Fig. 11-7. Samples of spectrally selective insulating glass units

glass will be radiated to the interior, in general, tinted glass is not as efficient as low-e glass (it will have higher emissivity than low-e glass).

Such coating will reduce the solar effect on the exterior warm pane to transfer heat across the cavity in IGU to the cooler interior pane through thermal radiation. The coating should be placed on the interior side of the exterior pane to reduce radiant solar heat transfer. Low-e coating does not necessarily affect T_v, although the coating can include other materials to reduce transparency as well. In climates with large cooling loads, the low-e glass should be combined with low SHG to reduce the cooling loads. This combination does not necessarily affect T_v as with tinted glass or reflective film or coating. In climates with large heating loads, however, high SHG is required with low-e coatings.

As an alternative to coating the glass surface, a technology has been developed that applies coating to a film surface and then places the film in the cavity of the IGU. One example is Southwall Technologies Inc.'s "heat mirror" IGUs (Fig. 11-8), which can have single or multiple film layers suspended within insulating glass units that can consist of various types of glass including low-e glass products (Southwall Technologies 2004). The coated film reflects the incident heat waves. The light transmissibility, however, is affected with degree of effect depending on the type of film. The basic property of heat mirror is to add thermal insulation. Therefore, just as coated glass, it can be used in different climates. For

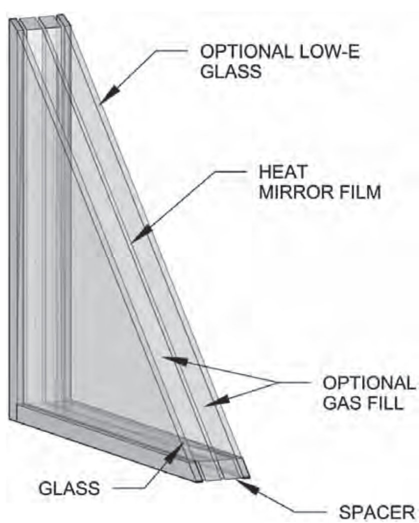

Fig. 11-8. Photo showing Sample of IGU with coated film within the air space (eeat mirror) and a drawing showing the layers

example, for climates with high heating loads, where high thermal insulation and high SHG would be needed, clear glass IGUs with heat mirror film should be used, whereas for cooling-dominated climates, where high thermal insulation and low SHG are needed, heat mirror film in combination with low-e glass works best.

Besides the coating technology that can reflect ultraviolet and infrared heat waves and reduce SHG, efforts to increase insulation of glazing systems have led to new technologies that add material with high insulation property within the IGU cavity. One such technology is to add aerogel pellets (e.g., Nanogel made by Cabot Corp.) in the cavity of double-pane glass or multiwall polycarbonate sheets (Schultz et al. 2005). Aerogel is made of a type of super-porous silicon foam with 97 to 99% air voids (Fehrenbacher 2006). In granular form aerogel is produced in 3 mm to 5 mm diameter pellets and can fill the air cavity in cellular sheets or between two parallel glazing lites (Kaushika and Sumathy 2003). The insulation property of aerogel is because of extremely small pores. The translucent aerogel particles can fill the cells of polycarbonate multiwall sheets (e.g., Duo-Gard) as shown in Fig. 11-9 or the cavity in IGUs to add insulation to the glazing and diffuse light, thus creating a translucent glazing.

Another technology that has been employed is incorporation of transparent cellular honeycomb array or panels within the cavity of IGUs (e.g., Solera by Advanced Glazing). Cellular honeycomb panels suppress the convection component of heat transfer between the two glass surfaces (Kaushika and Sumathy 2003). In Advanced Glazing's Solera configuration (Fig. 11-10), the honeycomb and the surface veil used to cover the open cells and diffuse light, are "hygroscopic" in the sense that at low temperatures the internal moisture is absorbed by acrylic and will not condense on glass surfaces. At high temperatures, however, the moisture

Fig. 11-9. Sample of multiwall polycarbonate sheet filled with aerogel

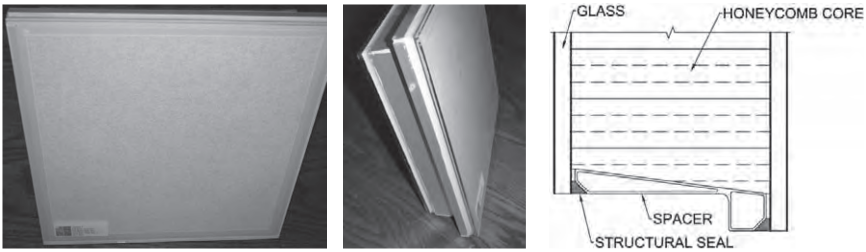

Fig. 11-10. Sample of glass panel configuration with cellular honeycomb array within the cavity between the two glass panes and a drawing showing the section details

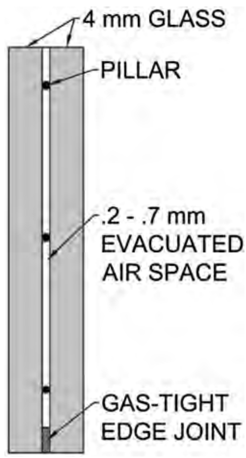

Fig. 11-11. Typical section detail of a VIG

is discharged through a breather tube that maintains the pressure equilibrium between the interior and exterior of the unit.

11.6 VACUUM-INSULATED GLAZING

Considering the success of the concept of insulating glass unit that benefits from the insulating property of air space between the glass panes, which can be further improved by filling space with argon or krypton gases, the use of vacuum instead of gas has shown great promise. By evacuating the air from the sealed space between the two glass panes, significantly higher insulation property may be created in IGUs. In general, the space between the two glass panes in vacuum-insulated glazing (VIG) is less than 1 mm, which is much smaller than that in conventional IGUs (normally about 13 mm). Fig. 11-11 shows the schematic section of a VIG.

The vacuum suction that is close to atmospheric pressure will tend to collapse the two glass panes on one another, and thus spacers (pillars) as thick as the cavity are needed at close intervals to keep the two panes apart. Low-e coating also can be applied to the exterior glass pane to further reduce heat gain. Currently, few manufacturers have limited VIGs on the market (e.g., Guardian Industries, Pilkington), but the availability is expected to increase in the near future. The u-value for VIG can be less than 0.2 Btu/hr-ft^2-°F as opposed to on the order of 0.5 for conventional IGU. The following references are suggested for additional reading: BuildingGreen (2008), Proefrock (2008), Zimmermann and Bertschinger (2001), Overend (2008), Marinov et al. (2001), and Weinlader et al. (2005).

11.7 CLOSING REMARKS

The discussion in this chapter reviewed various technologies for attachment of glass to the framing system. The chronological development of fastening mechanisms presented included putty, rubber gaskets, structural silicone, structural glazing tape, and lastly, point-supported glass. Each of the glass-to-framing fastening systems has some advantages and disadvantages when compared with other systems, with some systems more appropriate for certain applications. Curtain wall designers then have more than one option to choose from, which results in better and likely more economical design at the end. Besides efforts to develop new materials and techniques for fastening glass to frame, innovative design of the framing systems also have been under development. For example, the unitized framing system is a significant development in this area that can result in more economical designs because of the shop-glazing of the panels and speedy erection at the job site.

The double-skin façade system appears to have a great potential for more application in new building construction to provide both energy savings and improved indoor air quality. Furthermore, besides the various new glazing products and coating techniques that have developed to enhance energy savings, the use of photovoltaic on the building envelope, including on the glazing, is also expected to increase as a means of generating electricity. Overall, more and more glazing retrofit projects are expected to employ some of the introduced new technologies for energy efficiency.

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CHAPTER 12

SUMMARY AND CONCLUSIONS

Ali M. Memari

This primer has reviewed some basic concepts related to curtain wall and glazing systems with the intention of introducing this field to professionals interested in learning more about it without much prior knowledge. As the chapters were written by several authors, some overlap and perhaps slight differences in terminology, definitions, and discussion are inevitable. The authors who have different expertise related to envelope and glazing systems, including curtain wall design, fabrication, installation, performance, maintenance, forensics, and research have reflected their own unique experiences. In the following, each chapter is briefly reviewed to underline the issues covered followed by some concluding remarks.

Chapter 1 laid out the importance and significance of curtain wall systems, including the aesthetic it brings to the building and the reflectance and transmittance functions. It described the basic role of curtain wall as an envelope system to keep air and moisture out while providing a thermal-control mechanism and performing a structural function for resistance against wind load, live load, and seismic effects.

Chapter 2 introduced some basic terminology and systems used in practice and the most common curtain wall construction methods of stick-built and unitized systems, including the differences in fabrication, assembly, glazing, and installation. The chapter explained in detail the components of a curtain wall, including the vision glass, spandrel panel, extruded aluminum, framing members, materials (such as rubber or silicone used to attach glass to the framing), and sealants needed for waterproofing purposes, as well as materials used as thermal breaks to control cold spots that cause condensation on the interior surfaces of aluminum framing. The chapter further defined the terminology used to describe different framing members and their role in transferring loads to the structural system. Finally, the chapter briefly introduced the type of vision glass that can be used as infill as well as the main methods of attaching the glass to the framing: dry-glazing rubber gasket (capped system) and structural silicone glazing.

Chapter 3 expanded the material presented in Chapter 2 by providing further detailed definitions and elaborations on curtain wall components. The photographs and figures shown enhanced the explanation of the glazing and framing types and components including laminated glass and insulating glass unit, as well as different glass and aluminum framing types. The chapter also introduced the use of opaque material as part of some curtain walls, including stone, precast steel reinforced, or glass fiber–reinforced metal panels. Finally, the chapter gave a brief introduction to different curtain wall panel construction methods including dry glazed, wet glazed, structural silicone glazing, point-supported glass, and double-skin façade.

Chapter 4 discussed the testing of curtain wall mockups to evaluate the performance with respect to air and water infiltration, thermal performance, sound transmission, and structural resistance to wind loading and seismic racking, as well as debris impact. Relevant standards such as ASTM and AAMA that are followed for testing curtain wall systems were introduced. The chapter defined the differences between mockup testing in a controlled laboratory environment versus testing in the field and distinguished between visual mockups constructed to inspect construction quality versus performance mockup requiring various tests.

Chapter 5 presented a review of the principles needed to evaluate energy performance, including discussions of heat transfer and heat loss through curtain walls. The discussion clearly explained the concepts of heat conduction, convection, and radiation, as well as condensation issues. The chapter in particular presented a detailed discussion on the u-value in relation to heat loss determination by providing equations for the overall opening u-value and typical values of the u-value, solar heat gain coefficient, and visible transmittance for various IGU configurations. Furthermore, the chapter provided ample information that enhances the understanding of solar radiation and its effect on the interior and how it can be controlled, including the concepts of transmittance, absorptance, reflectance, and emittance. Finally, the chapter provided guidelines for thermal performance design of glazing for energy savings and an introduction to software available to evaluate optical thermal and solar performance of glazing systems.

Chapter 6 presented a discussion of issues related to waterproofing curtain wall systems, including design control of condensation and approaches to weep out and channel any rain penetration to prevent moisture-related damage. In particular, the discussion introduced software that can be used to evaluate thermal bridge situations that can lead to condensation. Guidelines to design and detail weep holes and flashing according to pressure-equalized rainscreen concept were presented for typical structural sealant glazing systems and unitized wall systems, including figures that show typical details by different commercial framing manufacturers to help better understand the critical detailing aspects for moisture management.

Chapter 7 discussed design of curtain walls to resist wind loads by providing design guidelines for curtain walls spanning floor to floor, including glazing, framing, connection assemblies, and anchorage to the structural system. Basic concepts and important parameters for determination of glass thickness and applicable guidelines were discussed. Furthermore, an introduction to mechanisms of attaching glass pane to framing based on continuous support using structural silicone glazing and isolated point support using point-supported glass technologies was given with emphasis on identifying critical parameters for wind load resistance. The chapter provided an overview of the wind design provisions in ASCE 7-10 and some general understanding of the role of curtain wall designer in the overall design process, including preparation of design criteria and appropriate code-related documentation. Finally, the chapter provided some guidelines based on practical experience for developing analytical models of the curtain wall and detailing issues related to connections, anchors, and fasteners.

Chapter 8 introduced basic concepts for understanding the behavior of glazing systems and curtain walls under seismic conditions. Lessons learned from the performance of glazing systems in past earthquakes were first discussed, followed by identification of parameters that affect the behavior of systems under earthquake-induced building interstory drifts. Building code provisions for seismic design of glazing systems were explained, including some simple examples showing application of the code provisions. Finally, mockup testing procedure according to the building code was explained and sample racking test results presented.

Chapter 9 can be considered an introduction to blast-load parameters of pressure distribution and impulse and quantitative and qualitative blast-resistant design of envelope systems and their application in design of curtain walls, including retrofit design parameters. Modeling of the glazing system based on simplified single degree of freedom or more detailed finite element modeling and dynamic analysis method and applicable blast design software were discussed. Design criteria to provide desired protection levels and glass breakage fragility curves used for design were explained. New and retrofit features for blast protection of the curtain wall components were described, in particular, schemes to mitigate injuries and casualties resulting from glazing systems such as the use of laminated glass, security film, and blast curtains. Finally, the chapter briefly discussed the topics of reliability analysis, risk assessment, resiliency, and life-cycle analysis as applicable to blast design of curtain wall systems and introduced relevant tools for risk assessment and asset resiliency estimation.

Chapter 10 described some recent innovative glazing and curtain wall technologies developed to address certain performance objectives, such as energy efficiency, independent or coupled with transparency or translucency, and introduced some tools for building information modeling used for design of complex skin geometries. This chapter reinforced many of the concepts discussed in previous chapters, including basic elements needed for energy efficiency design and detailing of curtain walls. Thermal breaks within aluminum framing, different low-e coatings, transparent or translucent insulation materials, vacuum-insulated glazing, and high-insulating window framing, among other technologies, were elaborated. Furthermore, active façade systems such as double-skin façades, active coating, or dynamic glazing (thermo-chromic, photo-chromic, electro-chromic), phase change material, building-integrated photovoltaic, and adaptive façades were explained. The class of innovative systems discussed also included envelopes with optical and thermal properties that can be changed in response to climates, occupant preferences, and building energy management control systems. New developments to create specialty transparent façades, such as cold-bent laminated glazing, flexible ETFE cladding, and polycarbonate panels, were introduced. Finally, a discussion on digital design, engineering, and fabrication of glazing systems for specialty structures and challenging forms was presented that explained the process of cold-bending trapezoidal quadrangles in free-form surfaces. Furthermore, the chapter introduced parametric façade design using 3D software tools that allow designing complex building envelopes and developing fabrication details and emphasized the importance of adopting building information modeling tools in such a design process.

Finally, Chapter 11 further enhanced some of the topics discussed in Chapter 10 and previous chapters by presenting a literature review on some of the new developments in glazing and the curtain wall industry. Specifically, the chapter reviewed mechanisms for continuous attachment of glass edges to framing systems and point-supported glass systems, double-skin façades, building-integrated photovoltaic glazing, and transparent and translucent insulation used in glazing systems.

As this summary of the 11 chapters indicates, today's curtain wall systems are significantly more complex compared with early simple window systems and may require input from various areas of expertise. Clearly the field of glazing systems is a fast-expanding area that incorporates many disciplines, including material science, architecture, and several fields of engineering (e.g., structural, mechanical, and electrical). Responding to the need of complex architecture, as well as sustainability and energy-saving goals, requires professionals with experience in different disciplines to be involved in all aspects of such envelope systems, including architectural design, material selection, system selection, structural design, energy design, fabrication, erection, insulation, maintenance, and forensics, as these systems are part of the envelope, which is the first line of exposure to and resistance against environmental effects.

The material presented in this book is intended to give an overview of the basic elements required for understanding of curtain wall and glazing system design, and it provides an introduction to various aspects, including material types and properties; design forces and methodologies with respect to wind, seismic, and blast; and design for performance such as waterproofing and energy efficiency. It also provides some familiarity with new developments and innovations in the field. The material presented is by no means extensive or discussed in great depth; rather, it gives the reader a reasonable understanding of the state-of-the-art and future trends in the field.

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Page numbers followed by *e*, *f*, and *t* indicate equations, figures, and tables, respectively.