Annual Review of Materials Research

Architectural Glass

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Annu. Rev. Mater. Res. 2022. 52:561–92

First published as a Review in Advance on May 13, 2022

The *Annual Review of Materials Research* is online at matsci.annualreviews.org

https://doi.org/10.1146/annurev-matsci-101321-014417

*1933–2021

Keywords

glass, windows, facade, environmental, structures, skyscrapers

Abstract

Recent decades have seen growing and widespread adoption of glass as an architectural material that can be used not only as window panes but also as facades, walls, and roofs. This is despite glass traditionally being considered a brittle material, not readily capable of handling the high loads required of architectural materials. Architectural glass has enabled the vaulted, transparent structures of many modern airport terminals and eye-catching buildings, such as the ubiquitous all-glass Apple Stores found around the world. Glass has enabled architects to expand their visions of buildings, using light and space to create wonderful new designs. As described in this review, these dramatic new possibilities for how glass is used in architecture have been the result of a convergence of many developments, including a better understanding of the fracture of glass, new processes for strengthening glass, confidence in large-scale finite element modeling of gravitational and wind loads, advances in the lamination of glass sheets, and the availability of ever larger individual sheets of float glass. The concurrent evolution of standards for the use of glass in buildings has also played a role in advancing the use of architectural glass. Advances in the architectural use of glass have their roots in the traditional uses and physical understanding of the properties of glass that have developed over hundreds of years.

1. INTRODUCTION

Glass is now being used in a nontraditional way by pioneering architects. In addition to its traditional use as windows to let people look out of a building and to let light in, glass is increasingly being used as a medium of artistic expression in addition to a building material (1–3). Terms such as "beyond transparency" are among those used to describe the architectural vision for more extensive use of glass. From the all-glass buildings of the Apple Stores in New York, Beijing, Istanbul, and Shanghai, to the glass facades of signature buildings and dozens of new airport terminals around the world (**Figure 1**), to glass bridge tourist attractions such as the Grand Canyon Sky Walk, the Zhangjiajie Grand Canyon Glass Bridge, and various other suspension bridges made of glass segments (4), these uses of glass would have been unthinkable just a few decades ago. As a building material, the simplest and most widespread use of glass in architecture is as a curtain wall—glass sheets in a metal frame (usually extruded aluminum or stainless steel mullions) hung from the main structure of a building that provide a facade but do not bear the structural loads of the building itself. Glass is most typically used as a transparent glazing material in the building envelope, including windows in the external walls. Glass is also used for internal partitions

Figure 1

Examples of high-profile buildings with glass facades. (*a*) The Shard, London. (*b*) Pudong skyline with a close-up (*c*) of the twisted façade of the Shanghai Tower. The building is unusual as inside the outer facade is an inner facade. (*d*) Jewel Changi Airport, Singapore. (*e*) The Apple Store building on Fifth Avenue in New York City following its reconstruction in 2012. Notice the absence of any steel supports. Photo in panel *a* reproduced from Colin/Wikipedia, **https://en.wikipedia.org/w/index.php?title=File:The_Shard_from_the_Sky_Garden_2015.jpg** (CC BY-SA 4.0). Photo in panel *b* reproduced from Wikipedia, **https://commons.wikimedia.org/w/index.php?title=File:Shanghai_skyline_from_the_bund.jpg&oldid=592805848** (CC0 1.0). The image of Shanghai Tower in panel *c* was taken from the giant-screen film *Dream Big: Engineering Our World*; copyright American Society of Engineers, courtesy of MacGillivray Films. Photo in panel *d* reproduced from Matteo Morando/Wikipedia, **https://en.wikipedia.org/w/index.php?title=File:JewelSingaporeVortex1.jpg&oldid=1020843512** (CC BY-SA 4.0). Photo in panel *e* reproduced from Ed Uthman/Wikipedia, **https://commons.wikimedia.org/w/index.php?title=File:Apple_store_fifth_avenue.jpg&oldid=536074570** (CC BY 2.0).

and to highlight architectural features. When used in buildings, glass is often of a safety type, including strengthened and laminated glasses. In other buildings, such as Apple Stores, glass is occasionally used as a structural load-bearing material as well. In both types of applications, the challenges are similar—the glass must support its own weight as well any structural loads and be able to withstand intermittent loads, such as from wind and vibration as well as thermal expansion. Increasingly, glass is also being used to provide an environmental barrier, facilitating control of the internal environment as well as absorbing noise without significantly altering visibility.

As described in the following section, eye-catching glass buildings were constructed toward the end of the nineteenth century in the heyday of world exhibitions, but very few were subsequently built until large flat sheets of glass could reliably be produced and methods for strengthening glass were developed to overcome its intrinsic brittleness. Once large glass sheets became available around 1960 with the development of the float-glass process, confidence in using glass as an architectural material grew and lessons were learned from highly publicized failures of glass windows, such as those in the John Hancock Tower in Boston in 1976 (5). Many of the windows in that 60-story building failed in high winds and fell on the pavement below due to very large stresses created by a combination of the aerodynamic pressures and inflexible fixturing used to hold the glass panes. In addition, the rigid fixturing used did not accommodate the thermal expansion stresses produced when the windows heated up in direct sunshine. In the Hancock Tower, the windows consisted of two panels of sheet glass, which were separated by a lead metal spacer bonded to silver coating on the glass and held in metal frames. In contrast, architectural glass today is usually of two types. One is a self-contained integrated glass unit (IGU) that is installed in a window opening or hung from a frame. The other usually consists of two panes of toughened (tempered) glass laminated with an intermediate thin bonding layer of a soft, compliant plastic or elastomer. This laminated glass combines the high strength of treated glass with the plastic interlayer to retain the shattered glass fragments in the event of the glass breaking. In addition, the increased scale of the float-glass production processes has enabled the fabrication of ever larger glass sheets. Finally, advances in fixturing have not only decreased thermal expansion stresses but also created cleaner-looking facades consisting of multiple individual glass panels. In addition, better modeling of glass strength, aerodynamic loads, and fixturing stresses has created greater predictive capabilities. The acceptance of glass for architectural purposes has also been facilitated by the development of standards and codes that prescribe the allowable use of glass, including some particular to locations where specific hazards, such as hurricanes, occur.

Key to the widespread use of architectural glass has been the mastery of structural design based on a thorough understanding of the mechanical properties of glass and the loads that the glass may have to sustain over the lifetime of a building. Advances in structural steel have also enabled much larger and stronger skeletal structures, and therefore higher skyscrapers, to be fabricated while also supporting the weight of the curtain walls. The development of skyscrapers was enabled by the architect Bradford Lee Gilbert (6), who realized that supporting a very tall building using bricks and mortar, which typically have low compressive strength, would require walls so thick that there would be little open floor space left at ground level. To overcome this predicament he created a cast iron frame to support the loads for the Tower Building on Broadway in New York. Because cast iron is much stronger than stone or brick when compressed, cast iron sections could be made much thinner while supporting the same load. (One drawback of using metal is that it softens in an intense fire and cannot then continue to support the building loads.) With this design innovation, the primary functions of the walls became keeping the rain out and controlling the internal environment. This is most notable in large skyscrapers, where the weight of the building is supported by a central core and the floors and facade are cantilevered out from the core with high-strength steel beams. This has required a continuous evolution in the strength of structural steels as buildings have become taller. In some of the most recent super skyscrapers, such as the Shanghai Tower, the concept of an environmental enclosure between two curtain walls, one inside an outer facade, is used to create a controlled atmospheric space, distinct from simply being a window.

In this article we review the advances that have made it possible for glass to be used in large-scale architectural buildings and draw parallels with advances in other materials. Although no attempt is made to be comprehensive, we start with a short summary of the historical use of glass in architecture since several important technological advances during that period have facilitated the large-scale use of glass structures today.

2. HISTORICAL BACKGROUND

Two historical examples of glass in architecture stand out from both an aesthetic and a technical perspective. One is the use of stained glass windows in medieval cathedrals, such as the magnificent windows at Sainte Chapelle in Paris (**Figure 2**). The other is exemplified by greenhouses built in the middle of the nineteenth century: Joseph Paxton's Crystal Palace in London built for the Great Exhibition of 1851, the Palm House in Kew Gardens in London, and the Pavilion at the World's Fair in Chicago. Sadly, of these, only the glass houses at the Royal Botanical Gardens in Kew remain. However, the new Gardens by the Bay in Singapore (**https://www.gardensbythebay.com.sg/**), with their two glass conservatories, and Dale Chihuly's Glass House in Seattle (**https://www.chihulygardenandglass.com/**) illustrate how architects continue to exploit the attributes of glass to create open and distinctive buildings (**Figure 3**).

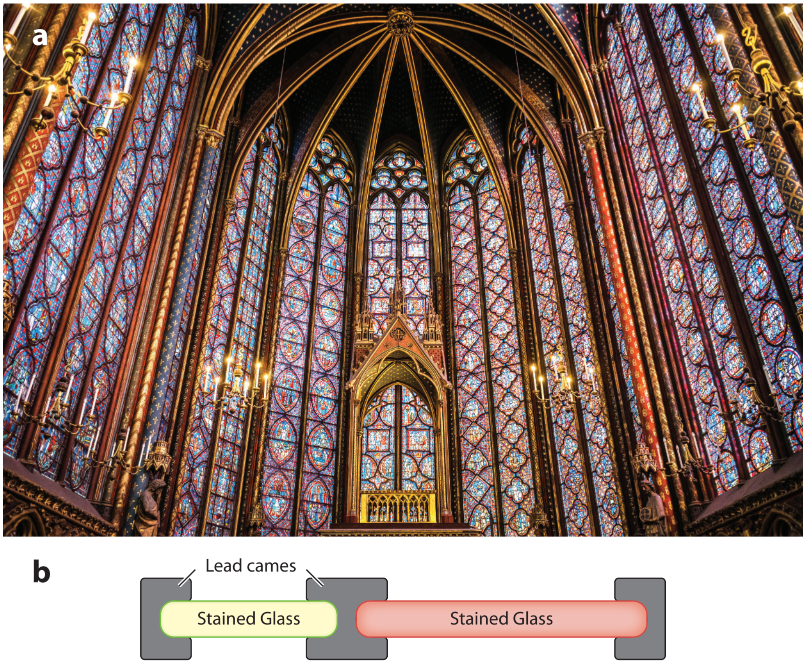

Figure 2

(*a*) Stained glass windows of Sainte Chapelle, Paris. Each piece of stained glass is held together with lead cames. Photo reproduced from Michael D. Hill Jr./Wikipedia, **https://commons.wikimedia.org/wiki/File:Sainte-Chapelle-Interior.jpg** (CC BY-SA 3.0). (*b*) Schematic of a section of a stained glass window showing two glass pieces held together with lead cames to prevent direct contact between the stained glass pieces.

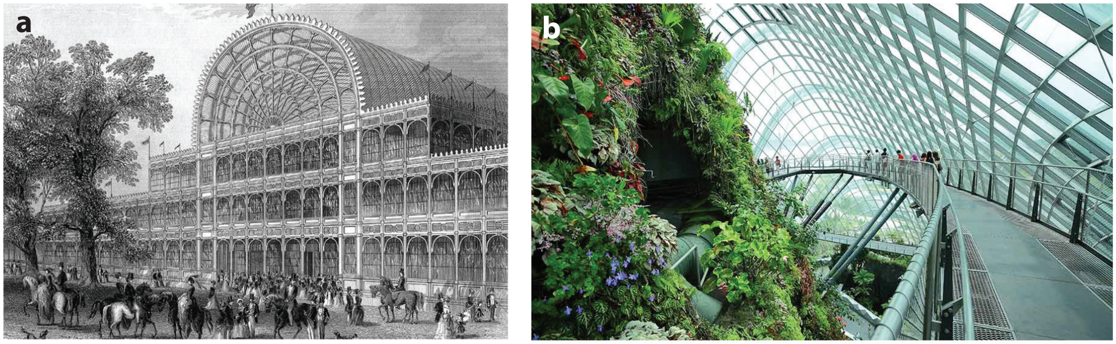

Figure 3

Images of (*a*) the Crystal Palace, London, in 1851 and (*b*) Gardens by the Bay in Singapore, 2021. Photo in panel *a* from *Tallis' History and Criticism of the Crystal Palace, and the Exhibition of the World's Industry in 1851* by John Tallis, 1852 (public domain). Photo in panel *b* reproduced with permission from the Singapore Tourism Information and Services Hub.

2.1. Stained Glass Windows

Although primarily constructed to glorify and illuminate religious themes, stained glass in medieval cathedrals demonstrated that glass could be used to create large-scale architectural features that also functioned as part of a building envelope, separating and protecting interior space from outside elements. Lacking the ability to make large pieces of glass, the materials innovation during early medieval times was to join much smaller individual pieces of stained glass together using leaded seams and joints. The function of these lead joints, formed from lead strips called cames, was to hold the glass pieces together and to accommodate flexural loading of the windows caused by wind gusts. From the vantage point of our modern understanding of fracture mechanics, the cames also function to provide a soft, compliant layer to prevent the individual glass pieces from coming into direct contact and creating localized stress concentrations, akin to Hertzian contact stresses, as described in Section 7.

The vivid colors of many of the stained glass windows also demonstrated a mastery of creating color in fired glass with the use of specific minerals, presaging the much later development of more refined and larger palettes of colored glasses in the fifteenth and sixteenth centuries. Colored stained glass was also created by painting colored glass powder (frit) onto the glass and heating it, presaging the development of glass coatings used today to add functionality. At the same time, it is worth noting that there were no extremely clear glasses, indicating that the artisans of those times were unable to purify the starting silica, lime, and other ingredients to prevent the incorporation of impurities, such as iron, that impart a greenish hue to glass (typically seen when viewed edge on). Iron is still a common impurity in glasses. Some medieval stained glass makers recognized that the greenish hue could be overcome by essentially oxidizing the iron ion impurities with the addition of manganese, but this knowledge was not widely communicated and may well have been a tightly held secret. There is also evidence that the glass makers of Santa Croce Basilica in Florence were skilled at fabricating multilayered glasses (7) to create different colors with desired intensities and hues, anticipating by 500 years the multilayered glass windows, lampshades, and other art nouveau pieces created by Tiffany in the latter part of the nineteenth and early part of the twentieth centuries.

2.2. Glass Houses

The Crystal Palace, constructed to house the 1851 Great Exhibition in London, was arguably the first large-scale use of glass for architectural purposes (**Figure 3**). Anticipating the wider use of a metal structure to support large areas of glass, the Crystal Palace was a monumental cast-iron and plate-glass structure two to three times the size of St Paul's Cathedral, the largest building in London at the time. Of particular significance, glass was used not only as vertical windows, where the loads are largely compressive, but also as balconies, flat roofs, and curved roofs, where the glass also has to withstand more complex loadings, such as bending and twisting, which create tensile stresses. The second innovation was the introduction of the sheet glass method into Britain by Chance Brothers in 1832 that made possible the production of large sheets of relatively cheap but strong glass. Some 300,000 panes of glass, mostly 4 feet long × 10 inches wide × 1 inch thick, were fabricated manually on site using the cylinder process. Strictly speaking, these innovations had been introduced some years earlier in the construction of two other glass houses, the Palm House of Kew Gardens built between 1844 and 1848 and the Jardin des Plantes built between 1834 and 1836, but not on the huge scale used with the Crystal Palace nor with the same widespread publicity and visibility. Anticipating manufacturing trends widely used today, the building was designed to be highly modular, consisting of individual 24-foot-wide units. This use of a modular, bolted cast-iron frame with glass sheets enabled the Crystal Palace to be dismantled, transported to another site, and then reconstructed miles away at Sydenham in 1854.

3. MECHANICAL DESIGN CONSIDERATIONS

The use of glass in buildings is now highly regulated by numerous US, international, EU, and Asian standards that stipulate the design codes for building envelopes and allowable stresses. Designs are typically based on linear elastic deformations with the spatial distribution of stresses computed from finite element codes for the building and component structures. Consequently, once design loads, such as those due to anticipated static structural loads and wind loads, are known, the stresses can be computed. Interestingly, glass has rather similar elastic properties to aluminum alloys as they have the same elastic modulus ($E \sim 70$ GPa) (**Table 1**), although unlike aluminum, which can deform plastically when the stresses exceed its yield stress, glass is brittle and fails once a critical stress is exceeded. Unlike designing with metals, concrete, or masonry, however, one of the difficulties in designing with glass is deciding on the allowable maximum stress since glass is susceptible to static fatigue. This phenomenon, the reduction in strength with the time under load, is well established and associated with the growth of preexisting flaws or cracks while glass is loaded (8).

Table 1 Material properties

Material	Young's modulus (GPa)	Poisson ratio	Density (kg/m^3)	Thermal expansion (ppm)	Thermal conductivity (W/mK)
Soda-lime glass	72	0.23	2,745	9	1.0
Aluminum	70	0.33	2,700	25	130
PVB (polyvinyl butyral)	0.0069	~0.5	1,100	22	0.2
Steel	210	0.30	7,900	12	50
Brick[a]	15–30	0.25	2,100	5–8	0.45
Concrete[a]	15–30	0.2	2,100	12–14	0.8
Wood[a,b]	8–20	NA	200–1,100	2–11	2–11
Nylon	1.5	0.35	1,140	50–90	0.26

Abbreviation: NA, not available.
[a]Wide range of values depending on specific material.
[b]Anisotropic properties due to anisotropic structure.

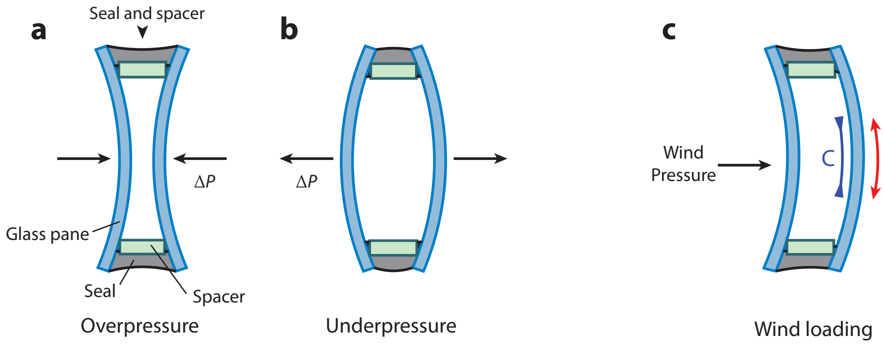

Figure 4

(*a*,*b*) Bending of a vertical double-pane window caused by pressure differences between the inside of an integrated glass unit (IGU) and the surroundings. (*c*) Wind loading also creates bending of the panes in the IGU. The bending creates both tensile (T) and compressive (C) stresses in the surface of the glass panes as indicated. Horizontal dimensions exaggerated for emphasis. Figure adapted with permission from Reference 10.

Although the static stresses can be computed readily, stresses due to pressure changes, wind loading, and thermal expansion are more challenging to compute, especially since wind loading–induced stresses vary with wind direction and velocity. These aerodynamic pressures obviously depend on the location and shape of the building, and if appropriate historical data are known, the wind loads can be estimated. The general problem is illustrated in **Figure 4** for a double-paned window held at its edges in a frame. In response to pressure variations, the flat glass panes will bend (flex) with respect to where they are held. Bending creates a stress distribution through the thickness of the pane, with a maximum tensile stress on the surface and compressive stress on the inside. For a given window pane thickness, the magnitude of the stresses depends on the wind pressure and increases with the third power of the window size (9), becoming especially significant for very large windows. If the tensile stresses exceed the strength of the window, it will crack and fail. A similar situation arises due to thermal expansion, for instance, due to the center of the window getting hotter from the sun than its edges in the frame. Since the frame is fixed, the constrained expansion of the glass as it heats up causes it to bend. Similarly, for a horizontal glass roof, gravitational loads, including from standing water or snow, also create bending stresses. In all three common situations, the response of the window depends on the particular way in which the glass is fixtured in the frame. As learned from the experience gained from the window failures in the Hancock Tower, a silicone rubber gasket in the frame imposes less constraint and hence more compliant fixturing than direct bonding to the glass.

It is important to emphasize that although the strength of the glass is an important design consideration, its post-fracture behavior often dictates the selection of the type of glass used. This is especially so where the fragments could cause a safety hazard, either as projectiles or as pieces falling on pedestrians passing below a window, for instance.

4. INDUSTRIAL DEVELOPMENT OF LARGE GLASS SHEETS

Despite the ubiquity of windows in buildings today, the development of large, flat panes of clear, distortion-free glass is relatively recent. Until about the 1850s, glass sheets were manufactured using one of two hand-blown processes, described below. These and other glass-forming processes rely on the ability to plastically shape glass over a range of temperatures and are based on the strong temperature dependence of the viscosity of glass, which is shown in **Figure 5**. Four temperature

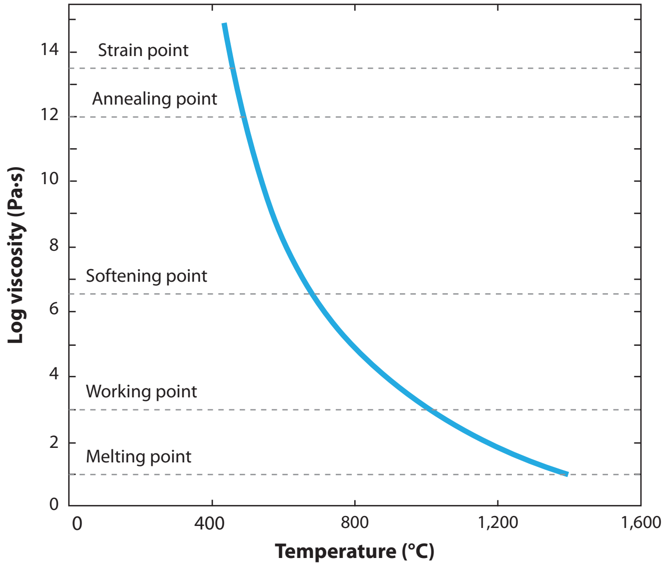

Figure 5

The manufacture of glass sheets relies on making use of the very strong temperature dependence of its viscosity. The data shown are for soda-lime glass, the usual window glass composition.

points are widely used: the working, softening, annealing, and strain points. These correspond to viscosities of 10^3, $10^{6.65}$, $10^{12.4}$, and $10^{13.5}$ Pa·s, respectively. The majority of glass-forming operations occur at temperatures between the softening and working points, as glass flows like thick honey at the working point but at the softening point will yield when pulled and sag under its own weight at a rate of 1 mm/min. The annealing point is the temperature at which internal stresses relax. The strain point corresponds to the maximum temperature at which glass does not creep and so is essentially rigid. While the dependence of viscosity on temperature has been quantified only in the last few decades, the conditions required to work with glass were established empirically well before on the basis of the color temperature of hot glass as seen by the eye.

Possibly the earliest method of making relatively flat glass was the crown glass process in which a glob of molten glass is gathered at the end of an iron rod, which is then rapidly rotated by hand. Under the influence of the centrifugal force, the glass flows, forming a disk with decreasing thickness toward its edge. When cooled, the thinned disk is broken from the rod, leaving a thicker center piece. The crown process was largely superseded by another hand-blown process in which cylinders of hot glass were first blown with a blowpipe, initially free-form but later into a cylindrical iron mold. The section thickness was further reduced by swinging the hot cylinder from a tall tower or above a deep trench under a combination of gravity and centrifugal force. Then the glass cylinder was allowed to cool before the ends were cut off and a cut was made along the side of the cylinder. Then, the two half cylinders were reheated to the working point temperature, allowing them to slump, by viscous creep under gravity, onto a flat metal surface, thus forming a flat sheet. The result was that much larger panes of glass could be produced with improved surface quality over a broad sheet, but imperfections still occurred. Surprisingly, the cylinder method remained a manufacturing process until the 1930s.

The first alternative process for manufacturing flat glass sheets was the Fourcault process introduced during the early 1900s. It rapidly superseded the others largely because it produced glass sheets that required little further processing except cutting to size. In the Fourcault process, glass

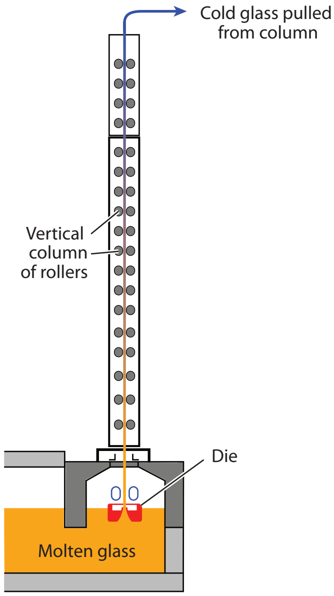

Figure 6

The Fourcault process for making continuous sheets of flat glass by pulling molten glass up through a slot die that defines the width and thickness of the glass. Figure adapted from VMH/Wikipedia, **https://commons.wikimedia.org/w/index.php?curid=25521631** (CC BY-SA 3.0).

is pulled up against gravity from a molten pool through a die that defines both the width and thickness of the final glass sheet (**Figure 6**). The glass cools as it is pulled up, retaining the shape defined by the die. This vertical draw process is the historical antecedent of the edge-defined film growth method (11) developed in the 1970s for the growth of shaped crystals directly from the melt, originally of sapphire sheets (12) for specialized windows and transparent armor and soon thereafter of thin silicon sheets.

The Fourcault method and other, related drawing methods developed by the Pittsburgh and Libbey-Owens companies were themselves eventually superseded by developments in machines for hot rolling of molten glass. Although it produces an inferior quality surface, rolling is a much faster process and more suited to the mechanization of the manufacture of large pieces. However, to produce glass sheets having both a uniform thickness and minimum optical distortion, the rolled glass usually had to then be ground and polished, an expensive and time-consuming process.

Today, large glass sheets are invariably produced by the float-glass process pioneered by Pilkington, which was prototyped in 1954 and began mass production in 1959 (13). One of the major technological advances in materials manufacturing in the twentieth century, this process enables large sheets of very flat glass with uniform thickness to be produced in a continuous process. Pilkington's key insight was that hot, molten glass, being a viscous material, would spread on a pool of molten tin to a constant thickness under a combination of gravity and surface tension forces. A key feature of the process is that molten glass reproduces the surface flatness and smoothness of the molten metal. Pilkington selected molten tin as the denser liquid because it has a substantially lower melting temperature (232°C) than the working point temperature of soda-lime glass (~1,000°C); a low vapor pressure, even above 1,000°C, the temperature at which the molten glass spreads; and a larger density ($\rho_t = 7{,}285$ kg/m^3). The equilibrium thickness, h_{fg}, of the glass produced is dictated by the balance between gravitational forces, which tend to thin the

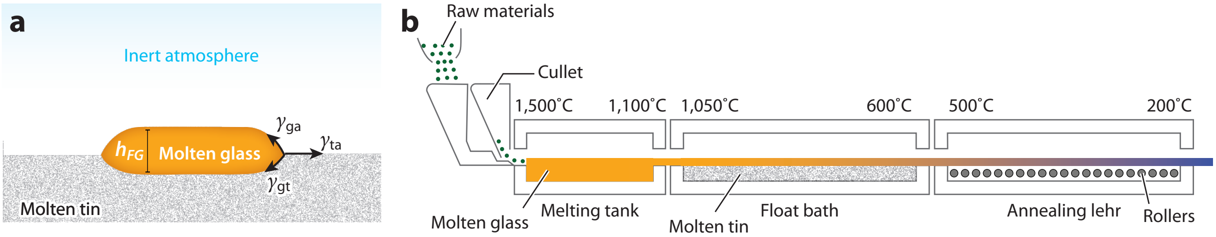

Figure 7

(*a*) The basis of the float-glass process is that molten glass is less dense than molten tin and thus floats, adopting an equilibrium thickness determined by the competition between surface tension and gravity. The glass surfaces are very smooth since they replicate the smooth surface of a liquid. Different thicknesses can be obtained by applying additional forces to the molten glass as it floats on the tin bath. Panel adapted from Reference 13 with permission from The Royal Society. (*b*) Schematic of a float-glass manufacturing line. Glass ingredients are melted at one end, floated out onto a molten tin bath, and pulled through a cooling zone in a self-supporting state before then passing through an annealing chamber (lehr) until it is cool enough to be handled by machine. An entire float-glass line is typically several hundred meters up to more than 1 km long. Panel adapted with permission from Reference 2; copyright 2002 Phaidon Press.

molten glass, and surface tension forces, γ, which tend to thicken the glass (**Figure 7*a***) (14, 15),

$$h_{FG} = \left[\frac{2\ \rho_t\ (\gamma_{\mathrm{ga}} + \gamma_{\mathrm{gt}} - \gamma_{\mathrm{ta}})}{g\ \rho_{\mathrm{g}}\ (\rho_{\mathrm{t}} - \rho_{\mathrm{g}})}\right],$$

where the subscript g, t, and a refer to glass, tin, and atmosphere, respectively.

For molten soda-lime-silica glass floating on molten tin under an inert, slightly reducing nitrogen/hydrogen atmosphere (chosen to avoid oxidation of the tin), the equilibrium thickness is close to 7 mm at 1,050°C. Sheets thinner or thicker than this are produced by a combination of external forces drawing down the glass as it is pulled from the float chamber and/or controlling the temperature of the glass surface (14). Because of such control of the manufacturing process, float glass is now routinely available in thicknesses from 2 mm to 19 mm. The largest sheets of float glass currently in production are believed to be 20 feet long by 10 feet wide, although sheets as large as 52 feet long have been produced for some signature buildings. The continuous casting process (**Figure 7*b***) also facilitates subsequent continuous coating of glass, for instance, to produce low-emissivity (low-E) glass and indium tin oxide (ITO) coating for electrical conductivity (see Section 10.2).

Thinner, even stronger glass can be produced by the Corning fusion process currently being used in smartphone displays and television screens. From the refining chamber, the glass flows into a tapered supply trough, which is deeper on its entrance side. Made of precious metals—platinum, iridium, etc.—the supply trough is resistant to corrosion by the molten glass. The glass overflows the inner sides of the trough and flows down its outer sides, forming two thin sheets. Because the trough is wedge shaped, the two sheets join at the bottom to form a single sheet and, still being molten, the surface between the two sheets disappears, leaving a thin sheet of glass with a surface that has never been handled physically and is therefore free of mechanical damage or chemical contamination, such as from the tin. As yet, however, glass made by this process, and that produced by the ion-exchange process, is not being used for architectural purposes. This is primarily because very large sheets are not being manufactured by either of these processes. It also remains to be seen whether there is any advantage in using this thinner glass for windows, as the majority of large windows need to be laminated for safety reasons and to withstand bending.

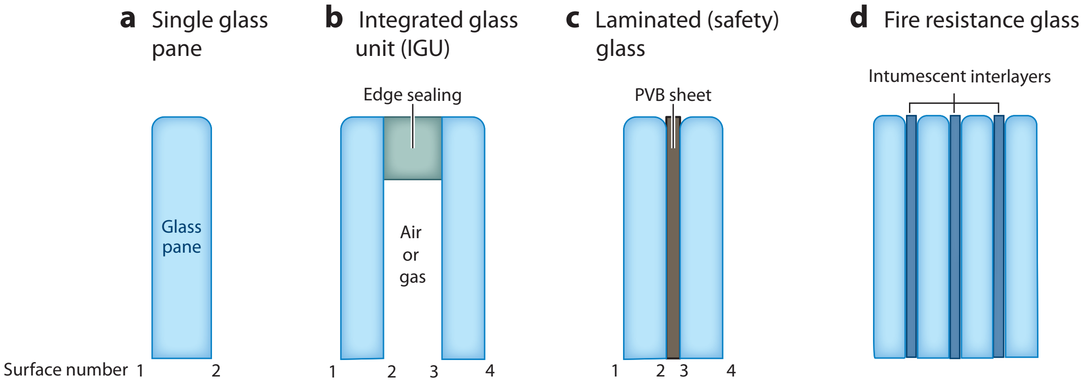

Figure 8

Cross sections of different glass formats from (*a*) a single glass pane to (*b*) an integrated glass unit and (*c*,*d*) two laminated glasses. Also indicated is the numbering of the surfaces, starting from the outside, that is conventionally used to describe which surfaces are coated. Abbreviation: PVB, polyvinyl butyral.

5. ARCHITECTURAL GLASS FORMATS

Although individual sheets (panes) of glass are still widely used as windows in many homes and offices around the world, increasingly, glass is used as a component in insulating IGUs or as laminated glass sheets, depending on the application (**Figure 8**). IGUs have obvious advantages as they allow for the sale and installation of standard size, prefabricated modular units that can be readily incorporated into buildings during construction or in retrofitting. Originally, IGUs were designed to provide thermal insulation by holding two glass sheets separated by a fixed-thickness air gap, and this was reflected in their name at the time, thermopanes. Increasingly, though, they have become the platform for introducing other functionalities. For instance, the air can be replaced by another, heavier gas, such as argon, to further decrease thermal conductivity, or one of the glass sheets can be treated with a low-E coating to reduce infrared heating or a dichroic coating to produce aesthetic colors. In an IGU, the glass sheets are typically held in a metal frame, usually aluminum, using a silicone rubber interlayer to evenly distribute the thermal expansion mismatch as well as mechanical loads and prevent contact between the glass and the metal frame. Undoubtedly, the introduction of the large-scale manufacture of aluminum mullions by extrusion in the 1970s facilitated the rapid deployment of IGUs. The silicone rubber is analogous to the lead cames used in making stained glass windows. In essence, synthetic rubber has also replaced the glazier's putty which had, in its turn, replaced the lead used to hold pieces of glass together and distribute loads to avoid Hertzian contact and breakage. As described in Section 6, there is also a growing trend of using laminated glass in IGUs to further enhance the functionality of windows.

6. LAMINATED GLASS

Laminated glass is generally the material form of choice for large-scale architectural installations, not only for safety reasons but also to provide greater bending stiffness to withstand wind-driven deflections as well as to provide greater thermal insulation. In its simplest form, lamination consists of two sheets of glass bonded together face-to-face with a transparent polymer sheet. Since its original development, it has become a technological platform for a wide variety of functional purposes ranging from noise abatement to force protection. Lamination also provides an opportunity to incorporate decorative motifs into the interlayer to give color or incorporate patterns or

Figure 9

Portion of the Montreal Convention Center illustrating the use of different colored laminate interlayers to provide color to the building while maintaining the strength and safety features of laminated glass. Photo reproduced from Moyogo/Wikipedia, **https://commons.wikimedia.org/w/index.php?title=File:Montreal_-_Palais_des_Congrès_-_20050330.jpg&oldid=601161631** (CC BY-SA 3.0).

script into a window or glass partition. It also enables a wide range of other interlayers, such as colored polymers, metal meshes, textiles, and customized patterns, to be embedded. An example is shown in **Figure 9** of the Montreal Convention Center, where individual windows each have a different color because different colored interlayers were used.

Historically, the development of laminated glass was motivated by safety considerations: the need to prevent shattered glass fragments produced by the impact of automobile windshields from injuring the driver and anyone else nearby. It was found that by laminating the glass with a continuous sheet of plastic, the glass fragments produced by impact could be held in place by their adhesion to the plastic. An early example of the manufacture of laminated safety glass was Triplex Safety Glass, originating in France and used as windshields for early motor cars. Originally, cellulose nitrate or Canada balsam was used to bond the glass sheets, but these polymers discolored over time. Now, polyvinyl butyral (PVB) is used almost exclusively as it has a similar refractive index to glass, is very clear, does not discolor with age, and forms a strong adhesive bond to glass. While the refractive indices of glass and PVB are similar but not identical (1.518 and 1.485, respectively), more important is that their wavelength dispersions are almost identical such that no interference colors form when viewed through the windshield at an angle. Other polymers, such as polyvinyl acetate, ionomers, polyurethane, and other proprietary compounds, are also used depending on the manufacturer, but PVB, with various modifications, remains the dominant interlayer material.

In the lamination process, two sheets of glass and a PVB sheet are pressed between heated rolls to form an initial chemical bond and subsequently autoclaved at 145–150°C for several hours at about 1 MPa to convert the PVB to a hard but clear layer. It is important that the lamination be carried out in a dust-free environment so that dust particles, which can scatter light, are not entrained, which would decrease the optical clarity of the laminated glass. The commonly used

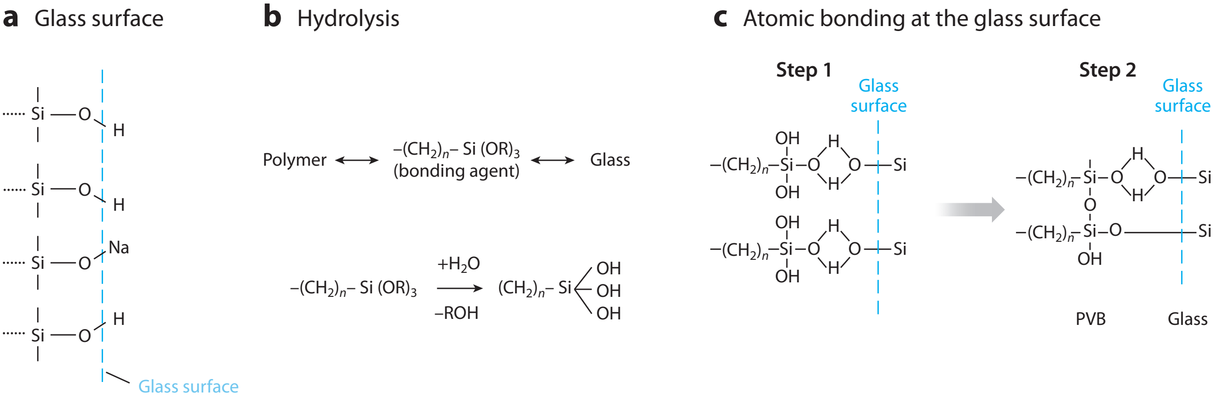

Figure 10

Schematic of the sequence of steps (*a* to *b*) associated with (*c*) the atomic bonding of the polymer interlayer to a glass surface during the lamination process. Figure adapted with permission from Reference 8.

PVB lamination polymer is, in fact, actually a copolymer of vinyl butyral, vinyl alcohol, and vinyl acetate. It is formulated to also contain a significant amount of a plasticizer to bring down the glass transition temperature of the pure PVB from 75–80°C to room temperature. This not only facilitates forming sheets but also increases the viscoelastic energy that can be dissipated during fracture and deformation of the laminate at ambient temperatures. Specialized additives, such as UV stabilizers and antioxidants, are also typically added to the formulation together with metallic salts to modify the adhesion to glass by forming metal ligands between hydroxyl groups of the PVB and the glass surface. The origin of the strong adhesion with glass is the formation of direct Si–O–Si bonds between the glass surface and the polymer after curing. Initially, the surface of glass is mainly covered in hydrophilic silanol groups (Si–OH) and hydrophobic siloxane groups (Si–OH–Si). Then, during lamination, the polymer and additives undergo a hydrolysis reaction, which then leads to (step 1) siloxane bonds to the glass and finally (step 2) a mixture of mostly siloxane and direct Si–O–Si bonds (**Figure 10**).

7. STRENGTHENING OF GLASS

It is common knowledge that glass is brittle and, although it is strong in pure compression, it readily breaks under tension at stresses of the order 10 MPa. Yet, if properly treated, glass fibers can exhibit tensile strengths of the order of 10 GPa, close to the theoretical strength of glass, making them among the strongest materials known. This apparent conundrum exists because the strength of glass is limited by the presence of microscopic surface flaws, generally far too small to see, that can act as incipient cracks. A quantitative theory of the strength loss due to flaws was developed by Griffith (16) in 1920. He was the first to point out that glass fails from small surface cracks and that the size of the cracks determines the distribution of the strength of the glass. He showed there was a relation between the strength of the glass, the size of the crack, and the energy needed to form the fracture surfaces. For a crack of length $2c$ subjected to a constant perpendicular stress, Griffith showed that there was a thermodynamic condition for its growth that corresponded with the condition that the energy lost by the stress field as the crack extended was equal to the increase in the surface energy of the extended crack. Accordingly, the strength of a brittle material, such as glass, is

$$\sigma_{\mathrm{f}} = \sqrt{\frac{2E\gamma}{\pi c}},$$

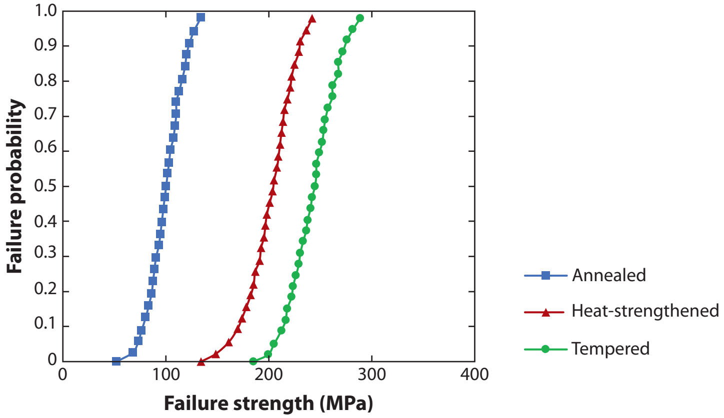

Figure 11

Cumulative failure distribution of small glass sheets evaluated in a ring-on-ring test, illustrating the statistical variation in strength of soda-lime glass after different heat treatments. Figure adapted with permission from Reference 18 (CC BY-NC-ND 3.0).

where σ_f is the fracture strength, c is the crack length, E is Young's modulus, and γ is the surface energy. Based on this analysis, the failure in brittle materials is caused by defects that act as concentrators of any superimposed tensile stresses, causing the incipient cracks to grow, resulting in failure. [Griffith's theory was subsequently generalized by Irwin (17) to form the basis of the field of fracture mechanics, used to help design the structures of all materials that will not fail.] In general, as it is not known which of many defects in a surface may cause failure, it is more useful to think of the strength of the glass surface rather than the glass itself. It then follows that processes that place the surface under compression will result in a glass that exhibits higher strength. (The alternative is to ensure that defects do not form and then protect the surface, as is achieved by cladding of optical fibers.)

One consequence of the fact that glass is brittle, and its strength is determined by surface flaws of unknown severity, is that glass has no well-defined strength. Rather, it exhibits a variation in strength even when processed in the same way. In fact, the strength of glass is best represented as a statistical parameter, and the failure probability distribution is best described by extreme value statistics, such as Weibull statistics, rather than a mean-value probability distribution, such as Gaussian statistics. An example is shown in **Figure 11**. The data were recorded from small samples with the consequence that the strengths are higher than those obtained in other tests. [Typically, the Weibull statistics are sensitive to the size of the samples tested (8).] Nevertheless, the probabilistic distribution in failure strengths and the rank ordering between the differently treated glasses are representative. For critical applications, designs are then based on the strength for a prescribed failure probability rather than a mean or average stress as is common with materials, such as most metals, whose strength is not dominated by the presence of defects.

The low strength of glass in tension provides an explanation for its sensitivity to breaking under contact and the necessity of using a compliant material, such as the lead cames in stained glass windows, to prevent pieces of glass from contacting one another. In one of the foundational contributions to mechanics, Hertz analyzed the stresses and displacements when two materials of different curvatures were pushed into contact (19, 20). The deformation field, visualized in **Figure 12**, is highly localized in the contact region and is principally compressive under the contact. However, large tensile stresses are generated at the contact periphery when a spherical object is pressed into a flat surface, giving rise to a ring of cracks that propagate as a cone crack (21). Rarely, however, is

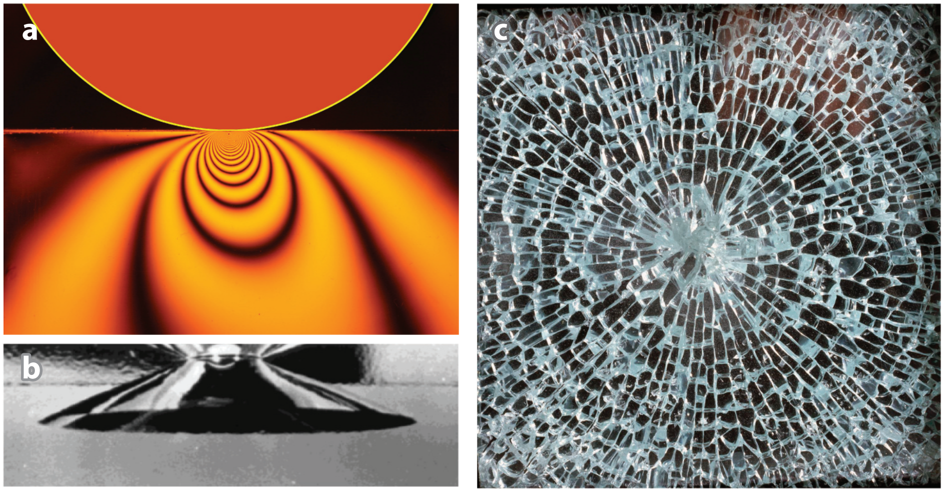

Figure 12

(*a*) Photoelasticity image of the stress localization produced in a flat surface when a hard, spherical contact (*top*) is pushed into it. Photo reproduced from Reibungsphysik/Wikipedia, **https://commons.wikimedia.org/w/index.php?title=File:Kontakt_Spannungsoptik.JPG&oldid=575806363** (public domain). (*b*) A cone crack produced in glass when indented by a hard sphere once the tensile stresses at the contact exceed the local strength, viewed from the side and just below the surface. Photo reproduced with permission from Reference 23. (*c*) The complex arrangement of intersecting cracks produced by the impact of a heat-strengthened glass. Photo reproduced from the Science Museum, **https://collection.sciencemuseumgroup.org.uk/search/objects/object_type/toughened-glass** (CC BY-SA 4.0).

the contacting object a hard sphere. More generally, the conditions for the onset of cracking, the subsequent propagation until the glass breaks, and the shape of the cracks have been extensively investigated using indentation fracture mechanics in which a sharp indenter, typically a diamond, is used to create cracks (22). These studies have guided the use of brittle materials, not only glasses, under a wide variety of contact conditions, including erosion, sliding wear, and machining. Two key findings are that soft, compliant materials buffer the contact, reducing the stresses produced, and that contact-induced cracking can be avoided or minimized by strengthening the glass.

7.1. Methods of Strengthening Glass

Although the identity of the surface flaws responsible for the low strength of glass sheets is not usually known, it is recognized that the surface of glass has to be treated so that it has a reproducible strength, a value that can be used to design with confidence. Depending on the treatment, three types of glass sheets are usually distinguished: annealed, heat-strengthened, and tempered (sometimes referred to as thermally toughened) glass. The treatments rely on the very strong temperature dependence of the viscosity of glass, a characteristic of all amorphous materials but particularly so of soda-lime silica glass, enabling residual stresses, stress relaxation, and flow properties to be manipulated by careful control of temperature and heating times (**Figure 5**).

Annealed glass refers to glass that has been heated to relax any inhomogeneous stress distributions, such as residual stresses produced during manufacture and subsequent handling, by viscous flow to minimize regions of maximum tensile stress. The process is analogous to the stress relief of metal parts by annealing except that the annealing mechanism for metals is through thermally activated dislocation motion whereas in glasses it is through decreasing viscosity, facilitating material flow from regions of compression to those of tension. Annealing is usually carried out by heating at a temperature close to the annealing point, 525°C for soda-lime-silica glass, and then slowly cooling to avoid creating additional residual stresses. The resulting glass is essentially stress-free throughout and clear, even when seen through polarized glasses.

The two other types of glass are heat treated specifically to place the surface of the glass under compression so that when subject to any tensile stresses, for instance, under flexing or impact, any surface flaws first have to overcome the compressive surface stress before they can propagate. The basis of this strengthening exploits the combination of the low thermal conductivity, the strong temperature dependence of viscosity, and the variation in the volume of glass as a function of temperature.

During strengthening, a glass sheet is heated while supported horizontally on rollers and shuttled back and forth so that it does not sag between the rollers. Then, when the glass is at a uniform temperature between the annealing and softening points (typically ~600°C), blasts of cold air are blown on both the upper and lower surfaces. The glass starts cooling rapidly on the outside, creating a parabolic temperature profile. (The parabolic temperature profile is a direct consequence of the sudden transient cooling and the small thermal penetration depth due to the low thermal diffusivity of glass.) As the outside of the glass continues to cool, it shrinks and its viscosity increases rapidly. Meanwhile, the inside of the glass also continues to cool and shrink but is constrained by the outer, stiffer region, which cannot relax because of its high viscosity, placing the interior of the glass into tension that grows in magnitude with continued cooling. The initial parabolic temperature profile of the glass gradually changes to a uniform temperature throughout the thickness of the glass while at the same time the stress profile becomes parabolic: tensile stress on the inside, compressive stress on the outside. At room temperature, the viscosity throughout is so high that this residual stress distribution cannot relax, leaving a parabolic residual stress distribution in the glass as shown in **Figure 13**. The difference between heat-strengthened and tempered glass is in the cooling rates used and, consequently, in the magnitude of the stresses produced. Made this way, the fully tempered glass can be up to four times as strong as the original annealed glass (24).

Creating a surface under compression increases the allowable tensile stresses that a window can withstand, whether the stresses are due to impact, thermal expansion mismatches across a window

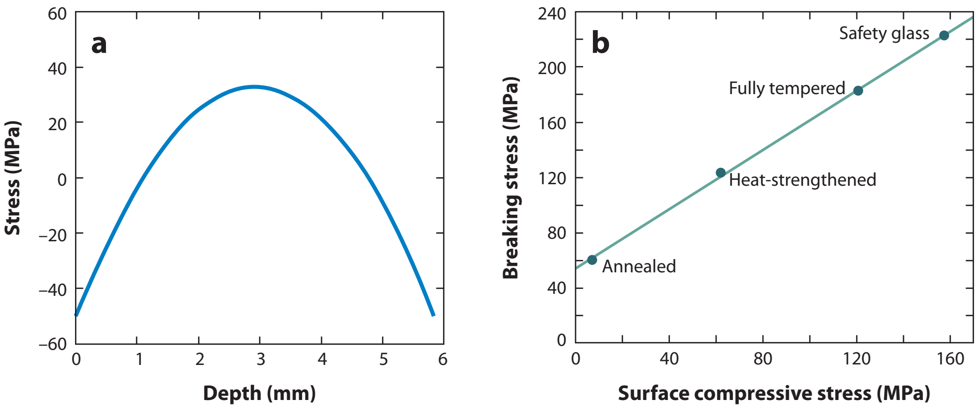

Figure 13

(*a*) Residual principal stress distribution through the thickness of a heat-strengthened sheet of glass. The surface regions are under compression, and the interior is under tension. (*b*) Average breaking stress of glass sheets as a function of the residual stress created in their surfaces by the heat treatment indicated. Surface compressive stress was measured using an optical polariscope. Figure adapted from Reference 24.

as a result of temperature variations, or flexural bending created by wind loading. Consequently, the glass doesn't break until an applied stress exceeds the sum of the surface compressive stress, σ_{surface}, and the flaw-dominated strength, σ_{S}. This is illustrated by the data in **Figure 13** showing that the breaking stress is linearly related to the surface compressive stress,

$$\sigma_{\text{bs}} = \sigma_{\text{s}} + \sigma_{\text{surface}},$$

as expected for the linear elastic superposition of stresses.

Not only are the failure strengths of the three types of glass different but, most significantly, so is their fracture behavior. Annealed glass will break into relatively few pieces whereas heat-strengthened glass will shatter into a large number of pieces. In marked contrast, tempered glass will explosively break into a huge number of pieces, as illustrated in **Figure 12*c***. The difference in fracture behavior is due to the large differences in elastic strain energy, U_{strain}, created in stressing the three types of glass. Because the strain energy, U_{strain}, varies as the stress squared,

$$U_{\text{strain}} = \frac{\sigma_{\text{f}}^2}{2E},$$

very large differences in strain energy can be created with tempered glass compared with annealed glass. Correspondingly, a larger strain energy is released on fracture.

7.2. Post-Fracture Deformation of Laminated Glass

As mentioned above, laminated glass was originally developed to prevent glass fragments, produced when a glass sheet breaks upon impact, from flying from an automobile window and injuring the occupants and persons nearby. The successful development of energy-absorbing laminated glass naturally led to its use in architecture as windows and other structures, such as partitions, where impact or overstressing is possible. Key to its success is that, unlike the brittle fracture of a single sheet of glass, laminates fail by a sequence of three events, two of which are highly dissipative. Once one of the glass sheets cracks because its strength has been exceeded, the crack is stopped by the polymer interlayer. Then, very rapidly, the strain energy in the stressed glass is released by fragmentation. After the glass in a laminate shatters, the polymer interlayer stays intact and, with further deformation, stretches, dissipating viscoelastic energy but maintaining adhesion with the fragmented glass pieces (25) (**Figure 14*b***). Essentially, this is similar to the energy dissipation mechanism exploited in metal/ceramic composites, such as those used in armor, and polymer matrix composites, where intact fibers span the matrix crack. Just as in those composite materials systems, the energy dissipated can be increased further by progressive debonding of the interface as deformation continues (26, 27). In fiber systems, this is maximized by the design of weak interfaces with the matrix. From these studies it is known that the energy dissipation involves both the stretching of the polymer and the progressive decohesion of the polymer from the individual pieces of glass (26). To maximize the energy dissipation, it is essential that the polymer/glass interface adhesion is not too high in order to allow the interface decohesion to occur as the polymer layer stretches, permitting an even greater volume of the polymer to deform. Because the viscoelastic dissipation as the polymer debonds and deforms is orders of magnitude greater than the fracture energy of the glass, the focus of much recent research has been optimizing the adhesion between the glass and the polymer interlayer (28). On the one hand, the maximum adherence is desirable to ensure that the glass fragments remain adhered to the PVB interlayer. On the other hand, less than maximum adherence is required to leverage decohesion and maximize energy dissipation. Many of the developments in optimizing the adhesion remain proprietary, but there is evidence that manipulation of the water content is important as it preferentially segregates to the glass/interlayer interface, forming bonds to the OH^- groups of the PVB (29).

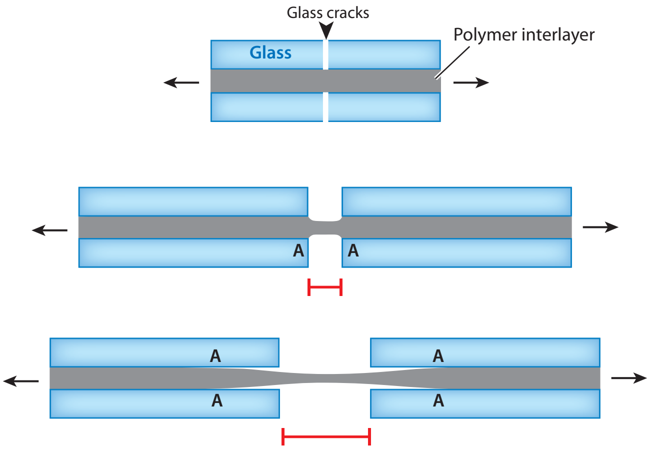

Figure 14

Mechanisms accompanying the fracture of laminated glass. Once the glass sheet fractures (*top*), the polymer interlayer stretches and dissipates energy. If the elastomer remains bonded at the glass fracture (*middle*), the maximum energy that can be dissipated is associated with the local stretching of the elastomer in between the crack faces. The red bar indicates the displacement of the crack faces. However, progressive delamination of the interface, A, along the faces of the glass pieces triggers even more deformation of the polymer interlayer, increases the volume of polymer being deformed, and amplifies the energy dissipation (*bottom*). From a mechanics perspective, there are significant parallels with the design of high-fracture-toughness composites through the design of weak interfaces.

The same energy dissipation principles have been utilized for designing windows where the kinetic energy of projectiles is likely to be much higher, for instance, to withstand damage from flying objects in locations prone to hurricanes and typhoons. To absorb the higher energies, one materials design strategy has been to use a multiple-sheet interlayer, a middle interlayer material selected to maximize the energy required to elongate it and a thin adhesion layer on either side to control the bonding between the interlayer and the glass. In essence, the two functions of the PVB interlayer in a standard laminated glass are replaced by two different elastomers. Typically, windows for buildings in hurricane areas are also designed with a thicker central interlayer to both increase dissipation on stretching and make the laminated window thicker and consequently more resistant to bending.

The development of glasses having even higher energy absorption capabilities, for instance, armor glass for resisting bomb blasts and aircraft windows, has been based on these simple concepts, but with increasing the number of energy-absorbing layers in multilayered laminated glass. For instance, the cockpit windows of the Airbus A330 (30) and Boeing 787 are made of multiple laminates of glass, acrylic, and urethane layers. The Boeing 787 glass-faced acrylic design features chemically strengthened glass as the face ply, stretched acrylic as the structural ply, advanced urethane technology, and anti-ice and antifog coatings.

It is important to distinguish between laminated glasses designed for resisting projectiles and those for withstanding bomb blasts. The former produces localized impact stresses whereas the latter gives rise to pressure waves. The wider use of glass in buildings, whether as an IGU or as structural features, has heightened attention to the behavior of laminated glass in explosive blasts (31), such as those that destroyed the Alfred P. Murrah Federal Building in Oklahoma City in April 1995 and more recently many buildings in Beirut, Lebanon. In the meantime, current blast-resistant windows are similar to those developed for projectile impact and consist of multiple laminated glass sheets held in stronger frames (32).

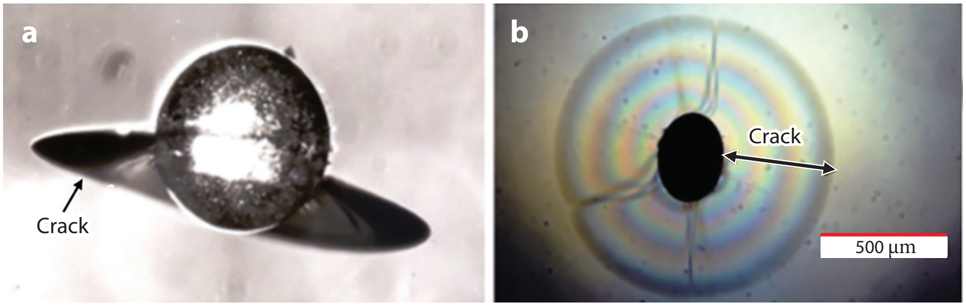

Figure 15

Cracks associated with nickel sulfide inclusions produced on heat treatment of a glass sheet. Note that, to clearly show the types of cracks produced, these images are of inclusions considerably larger than the critical size and would be readily detected by non-destructive evaluation during processing. Figure reproduced from Reference 36 (CC BY 4.0).

7.3. Spontaneous Fracture of Thermally Strengthened Glass

Although thermal strengthening to place the glass surface under compression has proven to be a highly effective, reliable, and scalable manufacturing process, failures still very occasionally occur, suddenly and long after the glass is heat treated, sometimes several years later. Indeed, it was only as a result of a series of spontaneous glass fractures in buildings in Australia well after installation that the origin of these perplexing failures was identified as being due to the presence of inclusions, notably nickel sulfide (33) (**Figure 15**). The nickel is believed to come from the stainless steel containers used in glass melting, and sulfur is not only a common impurity in the fuels used to melt the glass but is often added as a fining agent, such as Na_2SO_4. (A fining agent is added to reduce the nucleation of gas bubbles.) The sulfide inclusions can form during glass manufacture and occur during the float-glass process at random locations, including in the thickness of the glass where the compressive surface stresses are ineffective at suppressing crack propagation. The majority of inclusions are large enough that they are readily detected visually, and the affected portion of the sheet can be cut away and discarded. More problematic are small nickel-sulfide-based inclusions, especially those located in the center of a sheet. While these, too, can be detected, it requires far more stringent inspection methods, and even today some escape inspection and cause windows to eventually fracture spontaneously.

It is now known that the cracking is due to the volume increase, about 4%, that accompanies the $\alpha \rightarrow \beta$ phase transformation in nickel sulfide (34) as it is cooled below about 380°C. This is a sluggish, diffusional transformation that can take years to go to completion. Complicating matters is that the composition of the inclusions, $Ni_{1-x}S$, can vary substantially from the stoichiometric NiS composition according to the local trace concentrations of the nickel and sulfur in the glass. Furthermore, the size of the inclusions and the volume change can also vary significantly. As established by Swain (34), there is a critical inclusion size above which fracture can occur. The manufacturing conundrum is that the rapid quenching used in thermal strengthening does not give sufficient time for the α phase to transform completely to the thermodynamically stable β phase, and so the nickel sulfide can remain in a metastable state. Based on this metastability, one method of preventing the cracking is to anneal the glass in a subsequent, post-strengthening process at an intermediate temperature for a few hours. The idea of such heat soaking is to accelerate the transformation to the β phase so that it is completed by the time the glass has cooled to room temperature. Unfortunately, the selection of the appropriate time and intermediate temperature is far from straightforward since the heat soaking process also decreases the strengthening that can be produced by the thermal strengthening process. European standards originally introduced to codify the intermediate heat treatment—2 h at 290 ± 10°C—were later revised into a lower heat treatment temperature, 240 ± 10°C (35). Further refinements may well be introduced, especially for the largest pieces of glass, but these increase the manufacturing cost. Furthermore, the heat treatment usually has to be carried out before any subsequent coating so that the coating is not degraded by the heat treatment.

8. FIXTURING OF GLASS SHEETS

In many buildings, glass sheets in IGUs are held in a skeleton of metal frames that together form the curtain wall. This is usually the fixturing method adopted for very large vertical facades, such as on skyscrapers (**Figure 1**). As architectural applications have increased, laminated glass sheets can also be supported and held in place by bolting them to a structural support such as a load-bearing frame, a set of supporting cables, or even to one another. Several examples are shown in **Figure 16**. Many of these configurations can be used for horizontal and inclined roofs as well as for vertical walls and stairs. The fixturing can use either individual bolts or sets of bolts arranged in the form of a spider. On large curved roofs, such as railway and airport terminals, the laminated glass is supported from steel beams using cables connected to the spiders. Spider fixturing is designed to

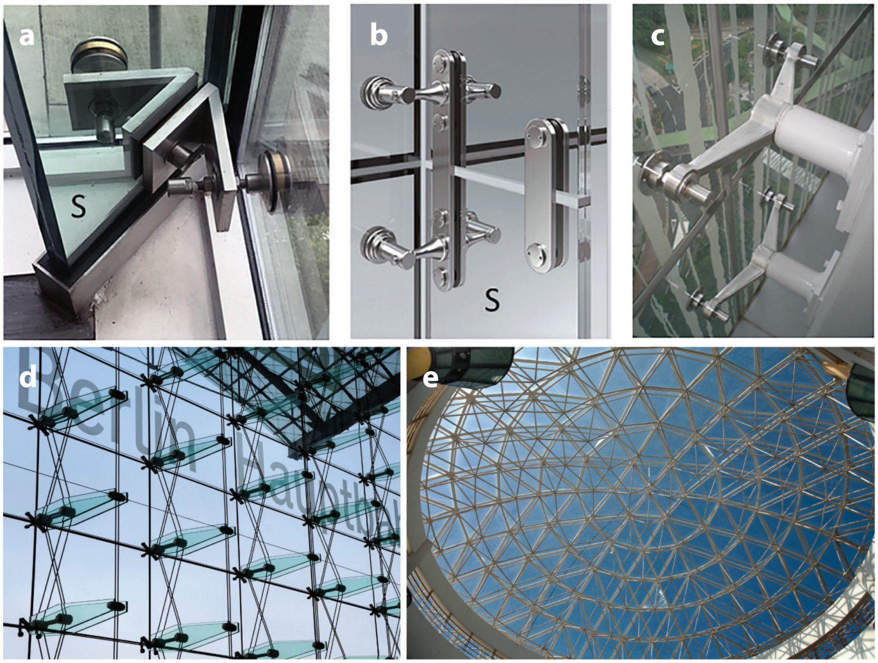

Figure 16

Fixturing glass sheets together using spider clamps. (*a*) Two laminated sheets at 90° are held in place by bolting them to a laminated glass flange, S, at 45°. This not only clamps them together but also provides stiffening and support. The black rubber washer spacers on the bolts and the setting in the stainless steel support of the glass flange are clearly seen. (*b*) One strip of sheet glass, S, bolted to four other sheets to stiffen them. (*c*) Two spiders holding laminated glass sheets to a steel column. (*d*) Glass curtain wall at the main railway station in Berlin with individual sheets held in place by a network of steel cables and braces. Photo reproduced with permission from Urbanmyth/Alamy Stock Photo. (*e*) Large glass dome with individual sheets held in place by tensioned steel cables and bolts. Panel *e* copyright Can Stock Photo Inc./alextan8.

absorb static and dynamic loads, including wind-induced flexure, and distribute the loads to the support structure without compromising visibility (10, 37).

In most of these fixtures, individual bolts, usually made of 316 stainless steel for its superior corrosion resistance, are screwed down to compress a gasket between stainless steel spreader disks to clamp against the glass sheets. This transfers the load from the bolt to the glass through friction. The purpose of the nylon (or other plastic, such as ethylene propylene rubber) compression gasket is to distribute load while simultaneously minimizing contact stresses that might otherwise cause cracking of the glass. The success of the bolt fixturing method also relies on developments in drilling smooth holes in a glass sheet, especially close to an edge, without causing microcracks as well as in subsequent annealing to remove any residual stresses, followed by heat treating the glass for surface strengthening. This bolting method of fixturing glass is akin to that traditionally used in joining materials that have limited strength in shear. These include anisotropic materials, such as wooden beams, as well as sections of brittle materials, such as ceramic matrix composites. An example is shown in **Figure 16*b***, where four wall segments are attached to a short perpendicular wall segment that itself is constructed from two laminated glass sheets held together with bolted steel strips with rubber gaskets in between.

The development of successful fixturing technologies is also the key to the fabrication of self-supporting glass structures, such as the Apple Store shown in **Figure 1**. In these structures, structural rigidity is provided by orthogonal glass flanges fixtured to the glass walls. Extra rigidity is also obtained in other glass structures by bolting two orthogonal laminated glass sheets to a 45° flange plate, as shown in **Figure 16*a***.

9. ENVIRONMENTAL CONTROL

As greater use is made of glass to create light and airy open spaces within buildings, ever greater demands are also being placed on minimizing energy consumption in buildings. In part this is driven by the recognition that the energy needed for heating, ventilation, and air conditioning (HVAC) now represents a major proportion of the energy use by society, in some cases second to only industry and transportation. It has been estimated that globally, HVAC currently accounts for half of the energy consumption in buildings and is likely to increase rapidly as air conditioning spreads to more countries (38). Furthermore, to facilitate an even larger number of air changes in response to coronavirus disease 2019 (COVID-19)-related restrictions, this energy use is likely to grow even higher. Together, these trends are of increasing significance since the thermal insulation provided by windows is far inferior to that of more traditional construction materials. To put these energy issues into perspective, it is useful to compare the thermal conduction of soda-lime glass with other construction materials. By itself, soda-lime glass is a relatively poor thermal conductor [$\sim$1.0 W/(m^2·K)]. This is not much greater than concrete [0.8 W/(m^2·K)] and about twice that of brick [$\sim$0.45 W/(m^2·K)] (**Table 1**). But since glass sheets are much thinner than these traditional construction materials, the net thermal resistance (R factor) is much lower, and the rate of thermal energy conducted through glass windows is correspondingly always greater than that through building walls. The rate of heat loss by conduction, $Q_{\mathrm{conduction}}$, through a sheet of material, such as a wall or window, is related to the temperature drop and the R factor of a sheet of material,

$$Q_{\mathrm{conduction}} = \frac{\Delta T}{R} = \frac{\Delta T \cdot \kappa A}{h},$$

where h is its thickness, A its area, and κ its thermal conductivity. For an IGU, the thermal resistances of the glass and the air gap are in series so the R value for the IGU can be expressed as

$$R_{\mathrm{IGU}} = 2R_{\mathrm{glass}} + R_{\mathrm{gap}}.$$

A more complete analysis would include the heat loss by conduction through the window frame, typically aluminum. Since aluminum is a far better thermal conductor than glass, the heat lost through the window frame cannot always be neglected.

Consequently, even with the improved thermal resistance of IGUs, thermal control becomes a major design objective, especially for buildings with a large area of windows, such as in many signature skyscrapers. Indeed, some environmentally concerned architects have called for a moratorium on the construction of large skyscrapers until improved methods of decreasing thermal losses are devised.

9.1. Thermal Control

To reduce the heat transfer between the inside and outside of a window, the first major innovation was the development of the IGU, in which air, or more effectively, a higher-atomic-mass gas such as argon, is trapped between two sheets of glass. (The thermal conductivity of a gas decreases with its molecular weight at fixed pressure.) Subsequently, the spacing of the glass panes is selected to maximize the thermal resistance of the trapped gas while simultaneously minimizing the convective flow of the gas within the cavity between the sheets (**Figure 17**). This optimization typically sets the spacing of the panes at 12 mm. This approach to minimizing thermal conduction has been extended by including a third sheet of glass to form triple-pane IGU windows, trapping an additional gas barrier in addition to increasing the overall thermal thickness of the window.

More recent innovations have come with the recognition that appreciable heat can also propagate through a window by thermal radiation so that the total rate of thermal flow through a window is

$$Q_{\mathrm{total}} = Q_{\mathrm{conduction}} + Q_{\mathrm{radiation}}.$$

The challenge in minimizing thermal radiation is that soda-lime glass is transparent to solar wavelengths, allowing sunlight to enter into a building, including the longer, near-infrared wavelengths that are not visible to the eye but still carry thermal energy. These energy ranges are illustrated in **Figure 18**, which compares the sensitivity of the eye to the incident solar spectrum. Two performance parameters are typically used in the design of windows (39), the visible transparency (VT) and the solar heat gain coefficient (SHGC). VT is the proportion of visible light (in the range

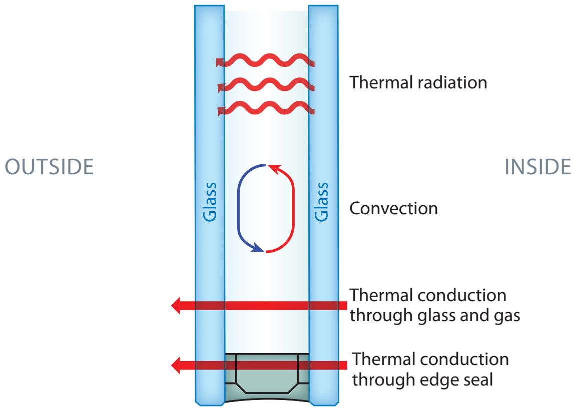

Figure 17

Schematic of the multiple parallel transport mechanisms by which heat can propagate through an integrated glass unit. Figure adapted from Reference 3 with permission from Birkhäuser Verlag GmbH.

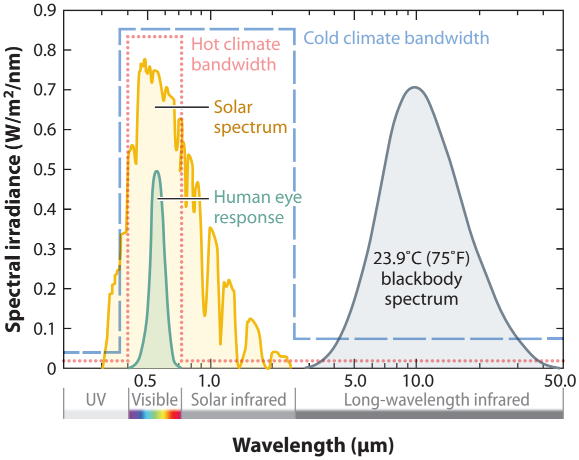

Figure 18

Variation of irradiance as a function of wavelength from the sun at sea level (*yellow*) and the blackbody irradiance of objects at room temperature (75°F). Superimposed is the spectral response of the eye. The two boxes outline the approximate transmission bandpass suitable for windows in a hot climate and the desirable bandwidth for windows suitable for cold climates that minimizes the transmission of solar infrared heating. Figure adapted with permission from Reference 40.

of 380–780 nm) that passes through the window. By contrast, SHGC is the fraction of the total incident solar radiation that passes through the window; a value of zero means no solar heat gain, and a value of unity means that all the incident solar flux passes through the window. This includes both the thermal radiation transmitted by the window and the radiative energy absorbed by the window material and subsequently reradiated in the transmission direction.

It is also desirable to minimize radiative losses from the building contents and walls to the outside. This occurs in the infrared regions, beyond 5 μm. To minimize these losses, the glass should be able to reflect the emitted radiative heat back into the room and also have a low E at these long wavelengths. Unfortunately, uncoated glass meets neither of these requirements as it has a high absorptivity (∼0.9) at almost all wavelengths, and consequently the windows will warm up to the temperature of the inside of the room and then radiate directly to the outside.

To minimize the solar heat gain by transmission through a window, low-E glasses have been developed and incorporated in IGUs. Strictly speaking, these are sheets of glass that have been coated by a multilayer stack of extremely thin metal and dielectric films specially designed to accomplish two functions while not adversely affecting transparency in the visible spectrum. One function is to alter the reflectivity of the glass in the near-infrared portion of the spectrum, denoted as the solar infrared region in **Figure 18**. The other is to reflect the long-wavelength infrared emission from the building interior back into the room to limit cooling at night. This occurs over a broad range of long wavelengths, as shown in **Figure 18** by the blackbody spectrum at 75°F. The multilayers are typically sputtered onto float-glass sheets as they are passed through a succession of separate magnetron sputtering units, each of which deposits a thin layer of a different composition. The majority of low-E coatings are based on incorporating one or more thin layers of silver, since this metal has a very high optical reflectance in both the visible and the infrared spectrum beyond 30 μm (41) and can be readily sputtered as a thin film. To be effective as a low-E coating, it must act much like an antireflection coating to block light, by optical interference, over the solar infrared spectral range. For this, the silver is sandwiched between layers of dielectrics, typically

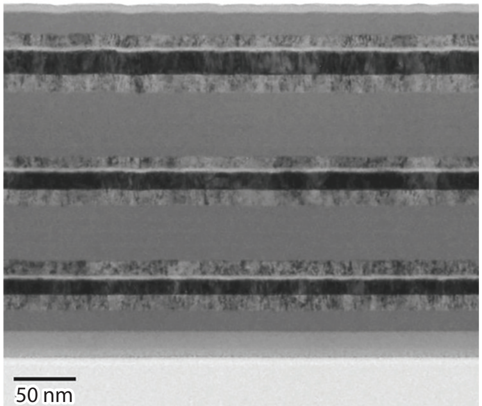

Figure 19

Cross-section transmission electron microscope image of a silver metal/dielectric multilayer stack on a soda-lime float-glass window used to decrease its infrared emissivity. The low-emissivity system shown consists of three layers of silver with intermediate ZnO dielectric layers and Ti adhesion layers, all deposited by sequential sputtering on a glass pane. Figure reproduced with permission from K. Burrows, Cardinal Glass Company.

oxides and nitrides (**Figure 19**). The effect of the sputtered multilayers on the optical transmission is illustrated in **Figure 20**, where the different glasses refer to different numbers of silver layers. One of the additional benefits of low-E coatings is that they also reduce the transmission of the UV component of the incident sunlight that is responsible for fading of colored fabrics. To protect the optical multilayers and provide scratch resistance, the optical multilayers are usually coated with a hard outer layer, such as amorphous silicon nitride or silicon oxynitride.

To further enhance the overall thermal performance, some IGUs have two low-E coatings, one on the inside of the first sheet of glass (surface 2) to control the solar infrared passing into the building and a second on the inside of the second sheet of glass (surface 3) to primarily reflect the long-wavelength radiation back into the room.

While impressive increases in effective thermal resistance have been achieved by these developments, opportunities remain to further reduce the thermal conductance, for instance, by replacing argon gas with a higher-atomic-weight gas such as krypton or xenon. Although such a substitution is technically straightforward, the increased cost and scarcity of these gases suggest this is neither generally economically viable nor sustainable. An alternative possibility would be to use an aerogel, but the transparency of aerogels cannot be maintained over many years, the warranty time of many windows. This is because the nanoscale porosity of existing aerogels cannot yet be stabilized and pore coarsening occurs even at room temperatures., As a result, the large pores grow and scatter light more effectively, and the aerogel becomes increasingly milky in appearance over extended periods of time. A separate but related practical problem is that improved thermal performance has led to increased propensity for water condensation, which is undesirable since it can not only impair visibility but also lead to mold formation. Indeed, condensation ratings are becoming standard in many window specifications.

9.2. Noise Reduction

In many building locations, such as near roadways, railways, and airports, reduction in outside noise is also an environmental concern, especially in the frequency range from ~50 Hz to ~10 kHz, the nominal range of human hearing. For the normal pressure component of the

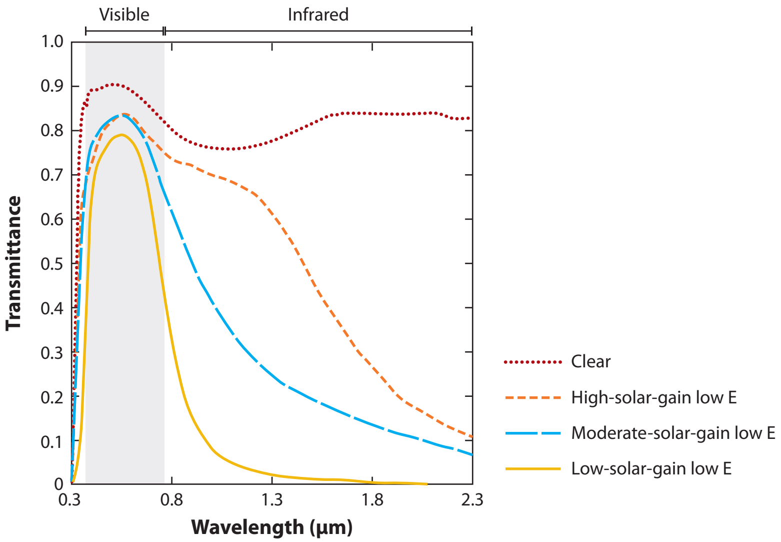

Figure 20

Transmittance of a series of low-emissivity (low-E) glasses illustrating how the transmittance in the near-infrared region associated with solar gain can be manipulated. In this graph, the decrease in solar gain in the near infrared is associated with increasing the number of silver layers. For comparison, the transmittance of uncoated glass (clear) is shown. Adapted from a graph created by Lawrence Berkeley National Laboratory (public domain).

incident noise, absorption is dependent on a mass-thickness effect so that the noise reduction (in decibels) increases linearly with frequency except over the range at which longitudinal waves resonate within the thickness of the glass itself. Over this range, acoustic wave interference causes a dip in the mass-thickness response curve, reducing the noise absorption (**Figure 21**). The frequency at which this occurs depends on the thickness of the glass.

The standard IGU configuration confers some noise abatement because the gas cavity between the two glass panes produces an acoustic mismatch at the interfaces between the glass and gas. In practice, this can be increased by using panes of different thicknesses so that they resonate at different frequencies, spreading the absorption dip over a broader range of frequencies. More effective reduction in sound transmission is achieved using laminated glass because of the combination of acoustic absorption within the polymer itself and the acoustic mismatch between glass and the polymer. The development of laminated glasses for improved noise reduction has exploited these contributions, increasing the thickness of the polymer interlayer to increase the volume of absorbing material and selecting polymer compositions that exhibit a higher acoustic absorption over specific frequency ranges, even though the optical clarity of the window may be compromised. For a planar pressure wave, the acoustic absorption and mismatch control the longitudinal transmittance through the mass-thickness effect. In many instances, though, the incident sound waves are neither planar nor at normal incidence and so cause local bending vibrations of the laminate. These, in turn, produce shear stresses in the polymer and additional noise reduction. Indeed, the larger acoustic losses in the 1,200–4,000 Hz frequency range, relative to a single sheet of glass and shown in **Figure 21**, are caused by viscous flow associated with flexing of the window. The acoustic damping is then determined by the loss factor (tan δ) of the polymer at the frequencies of interest (100 Hz to 5 kHz). For this reason, polymer developments have centered on increasing the loss factor of the interlayer materials, such as PVB, while not compromising its

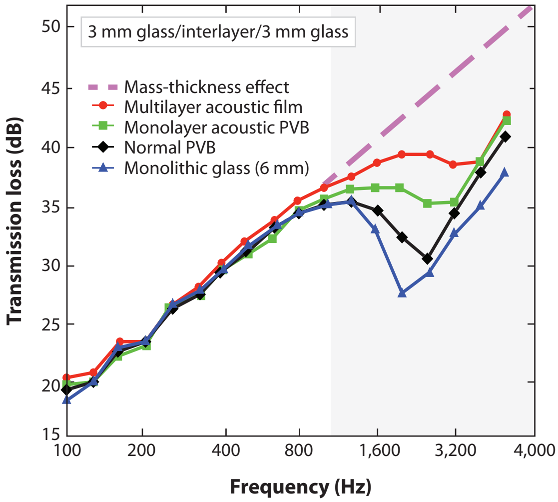

Figure 21

Comparison of the acoustic transmittance loss as a function of frequency for a laminated window composed of two 3-mm-thick glass sheets. The mass-thickness effect is represented by the dashed straight line. The dip around 2,000 Hz is due to resonance with the natural frequency of a 6-mm thick sheet of glass (*blue curve*). The gray shaded region is the frequency range over which the acoustic losses can be modified by manipulation of the properties of the polymer interlayer. Abbreviation: PVB, polyvinyl butyral. Figure adapted with permission from Yoshioka, Sekisui Chemical Company (42).

adhesion to glass. One very effective structural approach to increasing noise reduction even more has been to replace the single polymer interlayer with two or more layers containing different plasticizer concentrations, for instance, different concentrations of polyvinyl alcohol or polyvinyl acetate in PVB. Still further decreases in noise are achieved by using three glass panes so as to double the volume (and mass) of the polymer that absorbs the sound. This same principle is used in the design of windows for noise reduction and impact resistance in aircraft cockpits.

9.3. Fire Resistance

Glass is, of course, nonflammable and so, in principle, should limit the spread of a fire. In practice, however, glass windows can shatter because of thermally induced mismatch stresses that develop as the glass heats up, allowing a fire to break through and spread. In extreme cases, such as in rapidly moving brush fires, the glass can break by radiative thermal shock well before the fire reaches the windows. In either case, once broken through, a fire can continue to spread, so fire-retardant glass windows are really designed to delay the spread of the fire. Different levels of fire resistance, typically represented in terms of the time that a window delays a fire, are desirable depending on the specific design requirements. A common approach to increasing the fire resistance is to fill the cavity in an IGU unit with a transparent intumescent material, such as a gel, instead of argon. When exposed to a high temperature, typically in excess of 120°C, the intumescent material swells by foaming and decomposes, dramatically reducing both its effective thermal conductivity and its IR transmittance. Even though the glass panes may fracture, together the glass and the intumescent material form a more effective barrier to heat propagation through the window. Different intumescent layers may be used, but typically they include phosphate gels and sodium silicate, sometimes with a foaming agent. Ideally, the first layer is a thermally strengthened pane of glass attached to a polymer interlayer so that, even though the glass pane may fracture as a result of thermal shock, the fragments remain attached, hindering the blow through of the fire.

10. GLASS AS A SUBSTRATE FOR OTHER FUNCTIONALITIES

Low-E windows are, apart from mirrors and stained glass windows, the first examples of a new class of window products that use flat glass sheets as substrates for added functionalities. The successful development of large-scale manufacturing of low-E glass has opened up new opportunities for enhancing the functionalities of windows and is among the most active areas of research.

10.1. Tinted Glass

Tinted windows provide an aesthetic dimension for the architect as well as for other users of glass. There are two principal methods of coloration: One is to use a body-tinted float glass and the other, sometimes used in a complementary fashion, is to use a coating to produce a color or range of colors. Unlike stained glass windows, which were designed to be viewed in transmission of sunlight, today's windows are designed for both transmission and reflection. This greatly expands the possibilities for selecting the glass color and the placement of coatings. Commercial, body-tinted glasses are produced by adding small amounts of metal oxides to the molten glass in the float-glass process to take the metal ions into solution in the glass. These range from a greenish tint due to additions of iron oxides, to a bluish tint produced by a combination of cobalt and iron oxides, to gray or black tints due to different concentrations of iron, nickel, and copper oxides. These metal oxides are essentially the same as have been used for hundreds of years to color glass for vases and other ornamental purposes (43). This harkens back to the production of stained glass windows, which used much higher concentrations of ions. The colors are associated with electronic transitions of transition metal ions, and in some cases of rare-earth ions, in solution in the glass (44). Usually, the concentration of ions used in tinting float glass is small and is used to provide a slight color in transmission. However, there are notable windows, for instance, bronze-tinted windows, where selenium oxide is used (45). Despite using only low concentrations of additive ions, the concentration may nevertheless be sufficiently large for radiant heat absorption to modify the internal stress distribution across the width of a window, and consequently the thermal stresses almost always need to be taken into account in the window design to decrease the potential for thermal stress and breakage.

Especially attractive for visually striking facades are windows tinted by coatings that can also produce much stronger colors in reflection, such as those shown in **Figure 22**. Some of these appear to have one color in reflection and another in transmission. One particularly vivid example is the glass coating produced by the thermal decomposition of silane (SiH_4) gas on the hot glass during manufacture to create a very thin silicon film on the glass surface such that it appears silvery in reflection and bronze in transmission.

Figure 22

Examples of the use of different vivid reflective colors in skyscrapers in Hong Kong. The rightmost image is the Lippo Center, which has dark blue reflective glass.

At the other extreme, some architects demand a truly clear glass with no color. Since soda-lime glass commonly contains iron impurities that render a greenish hue, this can be achieved either by using very pure glass sources or by adding an oxidizing additive that neutralizes the green hue. This was first accomplished in the development of ornamental crystal and lead glasses. However, for the glass pyramid at the Louvre museum, the architect I.M. Pei selected a water-white glass. This is a special, low-iron-content glass. Exceptionally clear glasses can also be manufactured by using an antireflection coating on both sides so they also have extremely low reflectivity (<1% reflectance, compared with ∼8% for uncoated glass) in both directions and thus appear transparent. Such glasses are used in glass partitions in zoos and in windows to suppress reflections at nighttime at stadia and where the nighttime views are deemed impressive to suppress reflections at night. Depending on the manufacturer, antireflection coatings can be deposited by different methods. One is a sol-dipping process in which glass is successively dipped in different metal oxide solutions and then annealed at 450°C to 500°C (below the glass softening point) to create the multiple oxide layers.

10.2. Indium Tin Oxide–Coated Glass and Transparent Conducting Oxides

Most good electrical conductors, such as the free electron metals Al, Ag, and Au, are optically absorbing in the visible spectrum and so cannot be used as transparent, electrically conducting coatings on glass unless they are extremely thin. There is, however, a class of conducting oxides that are transparent in the visible and yet are electrically conducting. Principal among these are the ITOs, heavily doped, amorphous n-type semiconductors with a large bandgap in the range of 3.5–4.5 eV, depending on the actual composition (46). These coatings can be sputtered onto glass and have become the industrial standard for transparent electrodes in touch screens, displays, and smartphones as well as large-scale windows. Typically, for window applications, the ITO layer is itself covered with a hard, protective coating such as sputtered silicon nitride.

As indium is one of the scarcest elements in the earth's crust, there are efforts underway to replace ITO with other conducting oxides, such as Al-doped ZnO, or with percolative networks of conducting nanowires, such as silver nanowires and carbon nanotubes, embedded in thin, polymeric coatings. There is also extensive research underway into using graphene sheets as transparent electrodes. These percolative electrical networks are already beginning to find their first applications as electrodes in displays where the presence of defects can be masked or is less apparent. However, major improvements will be needed to reduce the optical nonuniformity when used as windows since the human eye is exceptionally sensitive to blemishes as well as variations in spatial transparency. This is much less of an issue in displays than it is in windows, where consumers have come to expect high clarity and uniformity.

10.3. Self-Cleaning Glass

In recent years, several major glass manufacturers have introduced self-cleaning windows. These are based on coating glass with a thin titania (TiO_2) film, usually deposited by magnetron sputtering or by chemical vapor deposition on what will be the external surface. Titania on glass confers two distinct advantages. The first is that it reduces the contact angle of water, increasing the propensity for water to sheet over the surface and carry away dirt rather than beading up into droplets. (The contact angle of very pure water on a clean, chemisorbed water surface on silica is zero but in practice lies between 8° and 14° for soda-lime glass windows exposed to air.) The second is that titania, most effectively in the anatase phase, acts as a UV-excited catalyst for the decomposition of carbonaceous deposits when exposed to sunlight. (The bandgap for titania is 3.2 eV.) In sunlight, the UV component creates surface oxygen vacancies in the titania, producing

Ti^{3+} sites that favor water dissociation and a hydrophilic surface. There are important parallels to the use of titania in dye-sensitized solar cells (47, 48). The detailed catalytic and decomposition pathways by which UV light promotes the photocatalytic conversion of carbon-based dirt to a gas, such as CO, and a carbon residue are not fully resolved. Ideally, this residue is washed away when it rains or the glass is cleaned. Nor is it established the type of dirt that titania is most effective in decomposing. Nevertheless, the prospect of effective self-cleaning windows for different regions of the world is an enticing possibility to reduce costs of cleaning, especially for very large areas, and will motivate research for years to come.

10.4. Electrical Control of Optical Transmittance

While the ability to control the optical transmittance of windows is still in its infancy as an architectural feature, there are several approaches actively being explored and, in some cases, being scaled up for applications, primarily as privacy windows (49, 50). They are all based on electrical control and the ability to apply a voltage through a coating deposited on glass panes of a window. For this reason, they generally are based on coatings deposited on ITO-coated glass, which provides the electrical backplane.

Among the best known are coatings that exploit the electrochromic effect (49, 51). These typically consist of an electrochemical cell of two tungsten oxide (WO_3) layers separated by an electrolyte layer. WO_3 is pale yellow as a thin film, with its electronic absorption band in the UV region. Under an applied electric field, it undergoes an electrochemical reduction and generates hydrogen ions on the positive side, which diffuse through the electrolyte and into the oppositely charged WO_3 layer. The result is an electrically controlled opacity with a blueish tinge familiar to those who have flown in Boeing 787s, which have windows with tunable electrochromic coating deposited on plastic rather than on glass. When the voltage is removed, the hydrogen ions diffuse back, and the coating becomes clear again. Despite the multilayer complexity, one advantage of these and similar multilayer electrochromic coatings is that they can be deposited by sputtering, as is already commercially proven for the formation of low-E glass. However, all electrochromic windows currently suffer from rather long switching times, typically minutes, an inherent limitation associated with ionic diffusion through the electrolyte.

Also under development are tunable transmittance windows based on electrically switchable polymer dispersed liquid crystals (52). The active coating consists of droplets of a liquid crystal dispersed in an optically matched amorphous polymer matrix. Liquid crystals are optically anisotropic and, when the droplets are dispersed, they have no preferred orientation, so their optical axes are at random. Consequently, the coating appears white as a result of the scattering of light between the matrix and the randomly oriented droplets. However, when a voltage is applied, the optical axis of the liquid droplets is aligned so that there is no optical scattering and the coating appears transparent. In contrast to the electrochromic windows, the switching can be fast (<1 s), but continuous electrical power is required to maintain the transparent state.

Although the electrically tunable windows under development control the amount of light transmitted, they either scatter the incident light or change the optical absorption, generating heat within the glass. None alter the reflectivity, and hence they cannot be used to lessen the solar heating within a building when the sun's intensity is high. For this, new approaches to selectively reflect infrared light when desirable are needed.

11. CLOSING REMARKS

The widespread use of glass as an architectural material is the result of a convergence of many advances in materials research. First and foremost have been technological innovations leading to the manufacture of very large, smooth sheets of high-optical-quality glass by the float-glass process. Complementing this manufacturing process has been the development of thermal treatments to strengthen the glass sheets by placing their surfaces under residual compression. This, in turn, has enabled confidence in designing glass structures based on maximum stress criteria. Together, the availability of large glass sheets having predictable strengths has formed the basis for two major innovation platforms. One is the use of float glass as a substrate for adding functionalities to the window, for instance, together with advances in multilayer coating of metal and dielectric layers on glass to control its optical emissivity, especially in the near infrared, for thermal management. The other major platform is large-scale lamination with optically transparent interlayers to provide capabilities that an individual glass sheet itself cannot provide. These include acoustic noise reduction, fire resistance, and post-fracture energy absorption crucial for safety assurance, including in hurricanes and even bomb blasts. Critical to the use of glass in architecture have also been the adoption and widespread implementation of the IGU as a standard format for integrating the functionalities into a single modular unit that can be arranged to create large glass envelopes and facades. Although the focus of this review has been on large windows, other architectural features, such as partitions, staircases, balconies, and elevated walkways, are now being routinely fabricated from laminated glass, further facilitating the use of glass beyond windows.

The growing acceptance of glass curtain walls, facades, and windows in buildings, including signature skyscrapers, and the opportunities they provide to architects suggest that there will be ever-growing uses of glass for architectural purposes. As there is no scarcity of silica, the principal ingredient of glass, and it can readily be recycled, it is one of the few sustainable large-volume materials. One impediment, though, is that glass's embodied energy cost is high, primarily because it needs to be processed at high temperatures (53). Nevertheless, there remain opportunities for further materials developments that promise even greater use of glass in architecture. For instance, with the increasing emphasis on energy efficiency, there will be even greater progress in minimizing heat loss through windows to reduce HVAC costs. This may be accomplished by methods of stabilizing the transparency of aerogels (54) to replace argon gas in IGUs or, more radically, by replacing glass itself with bleached, wood-derived cellulose embedded in refractive index–matched polymers (55, 56). New surface treatments or deposited films for improved longer-life, self-cleaning, and biocidal properties will be developed. It can also be confidently anticipated that current electrically tunable and switchable optical transmittance technologies will be applied to much larger windows as confidence grows and costs decrease with increased manufacture. Similarly, new glass processing methods that have led to the much higher strength glasses used in electronic device displays, such as Gorilla Glass, will be scaled up for use as windows as well as for window-based displays. Furthermore, with the advent of larger displays, privacy windows, and user-controlled coloring, for example, it is likely that architectural uses of glass will continue to expand, creating dynamic, visual environments for inhabitants of buildings.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

This article is dedicated to my coauthor, Shelly Wiederhorn, who, regrettably, passed away before we completed the manuscript. The idea of reviewing glass as an architectural material had its genesis in numerous conversations reflecting his lifelong curiosity, especially seeing the impact

that glass has made on our society over the course of his own, highly accomplished career in furthering our understanding of the fracture of glass.

LITERATURE CITED

1. Bell M, Kim JK. 2009. *Engineered Transparency: The Technical, Visual, and Spatial Effects of Glass*. New York: Princeton Archit. Press. 1st ed.
2. Wigginton M. 2002. *Glass in Architecture*. London: Phaidon Press
3. Wurm J. 2007. *Glass Structures: Design and Construction of Self-Supporting Skins*. Basel, Switz.: Birkhauser
4. Mairs J. 2016. World's tallest and longest glass bridge opens in China. *Dezeen*, Aug. 25. **https://www.dezeen.com/2016/08/25/zhangjiajie-grand-canyon-glass-bridge-haim-dotan-walkway-china/**
5. Roberts S. 2013. *The Wind Wizard*. Princeton, NJ: Princeton Univ. Press
6. N. Y. Archit. n.d. The Tower Building. *New York Architecture*. **http://www.nyc-architecture.com/GON/GON008.htm**
7. Verita M, Bracci S, Porcinai S. 2019. Analytical investigation of 14th century stained glass windows from Santa Croce Basilica in Florence. *Int. J. Appl. Glass Sci.* 10:546–57
8. Haldimann M, Luible A, Overend M. 2008. *Structural Use of Glass*. Zurich, Switz.: Int. Assoc. Bridge Struct. Eng.
9. Ashby MF. 2017. *Materials Selection in Mechanical Design*. Burlington, MA: Butterworth-Heinemann. 5th ed.
10. Achilles A, Navratil D. 2017. *Basics Glass Construction*. Basel, Switz.: Birkhauser
11. LaBelle HE. 1971. Growth of controlled profile crystals from the melt: part II. Edge-defined film fed growth. *Mater. Res. Bull.* 6:581–90
12. Ciszek TF. 1972. Edge defined film fed growth of silicon ribbons. *Mater. Res. Bull.* 7:731–38
13. Pilkington LAB. 1969. The float glass process. *Proc. R. Soc. A* 314(1516):1–25
14. Hynd WC. 1984. Flat glass manufacturing processes. In *Glass Science and Technology*, Vol. 2, ed. DR Uhlmann, NJ Kreidel, pp. 45–106. New York: Academic
15. Francis LF. 2016. *Materials Processing*. London: Academic
16. Griffith AA. 1920. The phenomena of rupture and flow in solids. *Phil. Trans. R. Soc. A* 221:163–98
17. Irwin GR. 1958. Fracture. In *Handbuch der Physik*, Vol. 6, ed. S Flügge, pp. 591–613. Berlin: Springer-Verlag
18. Lamela MJ, Ramos A, Fernandez P, Fernandez-Canteli A, Przybilla C, et al. 2014. Probabilistic characterization of glass under different types of testing. *Procedia Mater. Sci.* 3:2111–16
19. Johnson KL. 1987. *Contact Mechanics*. Cambridge, UK: Cambridge Univ. Press
20. Frank FC, Lawn BR. 1967. On the theory of Hertzian fracture. *Proc. R. Soc. A* 299:291–306
21. Tolanksy S, Howes VR. 1954. Optical studies of ring cracks. *Proc. Phys. Soc. B* 67:46–72
22. Cook RF, Pharr GM. 1990. Direct observation and analysis of indentation cracking in glasses and ceramics. *J. Am. Ceram. Soc.* 73:787–817
23. Roesler FC. 1956. Brittle fractures near equilibrium. *Proc. R. Soc. Lond. B* 69:981–92
24. Aben H, Anton J, Errapart A, Hodemann S, Kikas J, et al. 2010. On non-destructive residual stress measurement in glass panels. *Estonian J. Eng.* 16:150–56
25. Seshadri M, Bennison SJ, Jagota A, Saigal S. 2002. Mechanical response of cracked laminated glass. *Acta Mater*. 50:4477–90
26. Fourton P. 2019. *Adhesion rupture in laminated glass: effect of the interface and rheology of the polymer*. PhD Diss., Université Paris, Paris
27. Muralidhar S, Jagota A, Bennison SJ, Saigal S. 2000. Mechanical behavior in tension of cracked glass bridged by an elastomer ligament. *Acta Mater*. 48:4577–88
28. Fourton P, Piroird K, Ciccotti M, Barthel E. 2020. Adhesion rupture in laminated glass: influence of adhesion on the energy dissipation mechanisms. *Glass Struct. Eng.* 5(3):397–410
29. Tupy M, Merinska D, Svoboda P, Kalendova A, Klasek A, Zvonicek J. 2010. Effect of water and acid-base reactant on adhesive properties of various plasticized polyvinyl butyral sheets. *J. Appl. Polym. Sci.* 127:3474–84

30. PPG Ind. 2019. Aerospace transparencies. *PPG Industries*. **https://www.ppgaerospace.com/Products/Transparencies.aspx**
31. Hooper PA, Sukhram RAM, Blackman BRK, Dear JP. 2012. On the blast resistance of laminated glass. *Intern. J. Solids Struct.* 49:899–918
32. Vetrotech. 2021. Blast resistant glass. *Vetrotech*. **https://www.vetrotech.com/en-us/blast-resistant-glass**
33. Ballantyne ER. 1961. *Fracture of Toughened Glass Wall Cladding*. Melbourne, Aust.: CSIRO
34. Swain MV. 1981. Nickel sulphide inclusions in glass: an example of microcracking induced by a volumetric expanding phase change. *J. Mater. Sci.* 16(1):151–58
35. Karlsson S. 2017. Spontaneous fracture in thermally strengthened glass – a review and outlook. *Ceram. Silik.* 61:188–201
36. Kasper A. 2019. Spontaneous cracking of thermally toughened safety glass. Part one: properties of nickel sulphide inclusions. *Glass Struct. Eng.* 4:279–313
37. Fitechnic. 2017. Spider glazing. *Fitechnic*. **https://fitechnic.co.uk/spider-glazing.html**
38. Int. Energy Agency. 2011. *Technology roadmap—energy-efficient buildings: heating and cooling equipment*. Rep., Int. Energy Agency, Paris. **https://www.iea.org/reports/technology-roadmap-energy-efficient-buildings-heating-and-cooling-equipment**
39. Arbab M, Finley JJ. 2010. Glass in architecture. *Int. J. Appl. Glass Sci.* 1(1):118–29
40. McCluney RM. 1996. *Fenestration solar gain analysis*. Rep. FSEC-GP-65, Fla. Sol. Energy Cent., Cocoa, FL
41. Bennett JM, Ashley EJ. 1965. Infrared reflectance and emittance of silver and gold evaporated in ultrahigh vacuum. *Appl. Opt.* 4(2):221–24
42. Yoshioka T. 2017. Functional laminated glazing of passenger vehicle by advanced PVB technology - multi-layer technology for noise reduction and more. *Sekisui Chemical Company*. **http://www.s-lec.cn/product/architect/saf/paper/index.html**
43. Rasmussen SC. 2012. *How Glass Changed the World*. Heidelberg, Ger.: Springer
44. Vogel W. 1994. *Glass Chemistry*. Berlin: Springer-Verlag
45. Pilkington. 2021. Coated and tinted glass. *Nippon Sheet Glass Company*. **https://www.pilkington.com/en/us/architects-page/glass-information/coated-and-tinted-glass**
46. Grinley DS, Bright C. 2011. Transparent conducting oxides. *MRS Bull.* 25(8):15–18
47. Gratzel M. 2003. Dye-sensitized solar cells. *J. Photochem. Photobiol. C Photochem. Rev.* 4:145–53
48. Hagfeldt A, Boschloo G, Sun L, Kloo L, Pettersson H. 2010. Dye-sensitized solar cells. *Chem. Rev.* 110:6595–663
49. Granqvist CG. 2012. Oxide electrochromics: an introduction to devices and materials. *Sol. Energy Mater. Sol. Cells* 99:1–13
50. Shian S, Clarke DR. 2016. Electrically tunable window devices. *Opt. Lett.* 41(6):1289–92
51. Mortimer RJ. 2011. Electrochromic materials. *Annu. Rev. Mater. Res.* 41:241–68
52. Yang CH, Zhou S, Shian S, Clarke DR, Suo Z. 2017. Organic liquid-crystal devices based on ionic conductors. *Mater. Horiz.* 4:1102–9
53. Ashby MF. 2016. *Materials and Sustainable Development*. Oxford: Butterworth-Heinemann
54. Butts DM, McNeil PE, Marszewski M, Lan E, Galy T, et al. 2020. Engineering mesoporous silica for superior optical and thermal properties. *MRS Energy Sustain.* 7:39
55. Li Y, Fu Q, Yu S, Yan M, Berglund L. 2016. Optically transparent wood from a nanoporous cellulosic template: combining functional and structural performance. *Biomacromolecules* 17:1358–64
56. Mi R, Li T, Dalgo D, Chen C, Kuang Y, et al. 2020. A clear, strong and thermally insulated transparent wood for energy efficient windows. *Adv. Funct. Mater.* 30:1907511. Erratum. 2020. *Adv. Funct. Mater.* 30:2001291

Annual Review of
Materials Research

Volume 52, 2022

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