News

Bending Glass in the Parametric Age

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By Bill Millard

Gare de Strasbourg. Photo courtesy of Sedak.

The inherent strangeness of glass has been an undercurrent in architectural thinking at least since the days of Paul Scheerbart (1863-1915), the German speculative-fiction author who influenced (among other things) Bruno Taut's expressionist Glass Pavilion and Walter Benjamin's Arcades Project. Scheerbart believed that buildings made predominantly of glass could alter human perception and even usher in a utopian era.

Today's glass-forming technologies are expanding the sculptural and functional possibilities of this distinctive material. The built environment may never become as culturally transformative as Scheerbart hoped, but as hot and cold glass-bending methods continue to evolve, architects' material repertoire is expanding to invite and transform light in ways that even fin de siècle visionaries couldn't have imagined.

Mighty at the Molecular Level

Physicists classify glass as a noncrystalline amorphous solid, lacking the orderly organization of crystalline solids. Sameer Kumar, AIA, LEED AP, who serves simultaneously as director of enclosure design at SHoP Architects in New York, visiting lecturer at the University of Pennsylvania, and visiting assistant professor at the Pratt Institute, describes glass as “more of a liquid structure in solid form, which causes a number of difficulties in accounting for its strength.” Since glass differs from other materials at a molecular level, Kumar notes, it handles stresses differently; its response to excessive force is to fail “catastrophically, immediately” instead of displaying elasticity as steel does. “Its strength is statistical strength, not material strength,” he says. “We never use the true material strength of glass for calculations; we only use probability of its breakage.” These properties help determine its utility in different architectural settings.

Taut’s Glass Pavilion, built in 1914 for the CologneDeutscher Werkbund Exhibition.

When either thermally or chemically tempered, glass is surprisingly strong. “There has always been a little bit of hesitation,” Kumar allows, “but as you understand the glass, naturally it becomes more and more possible to use it structurally.... It basically has these microscopic cracks all over the surface, and when you put stress into glass, if you bend the glass, its strength is as good as the weakest crack traveling through.” Tempering works by tightening these microscopic cracks, putting the surface into compressive stress and the inside into tensile stress. (This is the same reason a Prince Rupert's Drop, a tadpole-shaped oddity created when a drop of hot liquid glass is rapidly cooled in water, contains internal forces strong enough to explode.)

Apple Stores, at locations such as Fifth Avenue in New York City, are driving ambitious bent-glass applications and innovations in the United States. Photo by Anthony Quintano.

The combination of lamination and tempering, Kumar notes, allows the ambitious applications widely seen in Apple stores, such as staircases and other load-bearing elements. One catch in heat-tempering bent glass is that current equipment, which moves heated and softened float glass on a cradle through a furnace with jets of cold air beneath for rapid cooling (putting the material into permanent internal tension, forcing the cracks closed as the surfaces and the soft core cool at different rates) limits this process to radial curvatures. “You can adjust the shape of these jets, but they end up always being a curvature of a circle,” he says.

The less common alternative of chemical tempering, which strengthens a glass surface through chemical reactions (usually in a bath of a potassium solution, which replaces sodium and forces itself more tightly into the microscopic cracks), is slower and costlier but compatible with more types of curves. It is about three times as strong as heat-tempered glass, according to Peter Arbour, Assoc. AIA, a glazing specialist formerly with RFR Consulting Engineers and Seele, now a senior consultant at Vidaris. Chemical tempering also yields more consistent optical properties, lacking the distortions that can appear during cooling. “The spiral bent glass guardrails at the Apple Store on Fifth Avenue are chemically tempered glass,” Kumar reports; “that glass could not be thermally tempered.”

Chemically tempered glass does not change its breakage pattern as heat-tempered glass does (crumbling into cullet instead of breaking into sharp shards like annealed glass) and is thus not defined as safety glass according to building codes. However, says Kumar, chemical tempering can render glass much stronger than either laminated or heat-tempered safety glass. Corning's Gorilla Glass (familiar from smartphones), an extremely thin alkali-aluminosilicate sheet glass made by immersion in a hot potassium-salt bath, is only beginning to find architectural applications; it is unusually flexible, and Kumar sees it as a potentially important building material of the future. The same firm's Willow Glass, Arbour says, is flexible enough to roll up like plastic but is not yet used in buildings.

Hot vs. Cold: As Conditions Require

When its microscopic cracks are overcome, glass has considerable elasticity. “We don't have any evidence that glass in any way deteriorates over time under stress, because [with] fully tempered glass, you're putting the glass in stress,” says Kumar. “By bending it, you're just putting it in a little more stress than what it contains, unless you're talking about radical curvatures.” This property allows the counterintuitive process known as cold bending, which produces curved glass units more economically than hot-bending processes such as slumping, in which heated glass rests on molds in a large kiln and takes its shape from them, either with the help of gravity or with an additional mold on top. Cold bending is so much less expensive than hot bending, Kumar says, that “if we can get away with cold-bending glass, we will always get away with cold-bending glass.” Laminated glass can be either cold-bent or heat-bent in a slumping process; after heating of both layers to a precise fit with an insulating fabric between them, the layers are bonded together in complex shapes by another transparent material, often polyvinyl butyral.

“We've all seen glass bend a little bit,” Arbour says, “and it probably bends more than most people imagine.” Within limits, which he estimates conservatively at approximately 1:1,000 (thickness to curvature radius, i.e., glass 8 mm thick can be bent up to an 8-m radius before failure), this property allows cold forming, drastically reducing the energy required to achieve curvature. Cold-bent glass in a single pane recovers its original flatness when released; “it has no memory of bending” and does not take and hold a shape. This means that cold bending requires a closed frame that holds it in place; this method is better suited to gentle curves and large scales. While cold bending is feasible with either single panes, laminates, or insulated glazing units (IGUs), the long-term integrity of IGU aluminum spacers, moisture seals, and structural silicon can be another constraint on the amount of bending. These IGUs are typically warrantied for 10 years, Arbour observes, but can last 25 when correctly installed and maintained. Cold-bent insulating glass, Kumar cautions, can be susceptible to edge shear that compromises polyisobutylene hermetic seals: “If you were to take the edge of an IGU and squeeze it really hard, you would basically squeeze the butyl out of the edge like a tube of toothpaste, and that would cause failure of the IGU. When you try to cold-bend an IGU, there's a very small area where you can do it while ensuring that the butyl will not be squeezed out. That is the primary hurdle when doing a lot of cold bending of façades.”

Arbour has experience with both hot and cold bending processes and recognizes certain buildings, including several in New York, that illustrate the virtues of each. The complex curved glass partitions in Frank Gehry's Condé Nast cafeteria at 4 Times Square building, Arbour observes, were double-curved heat-formed glass created with two-sided molds. The façade of Herzog & de Meuron's 40 Bond Street, a project Arbour worked on, uses bottle-green laminated glass with tight bell-shaped heat-bent curves to accentuate its grid pattern, simultaneously concealing the building's structure and highlighting it in a gesture evoking lower Manhattan's traditional cast-iron frames. Gehry's IAC headquarters uses cold-bent glass in IGUs, with distinctive white fritting adding to the building's nautical motif. “Flat sheet materials do not receive double curvatures easily,” Kumar adds, and warped corners like those of the IAC's panels only “approximate a true double curvature”; heat-bent glass will usually give better optical quality and more predictable reflections. Irregularities, he says, are visible in the IAC's façade under certain light conditions; the IAC's uneven reflections of Jean Nouvel's nearby 100 Eleventh Avenue, with its prominent grid pattern, indicate the optical limitations that can appear with cold bending.

Frank Gehry's IAC Headquarters in New York utilizes cold-bent glass in IGUs to approximate true double curvatures. Photo by waywuwei.

The Gare de Strasbourg in Bas-Rhin, France ultilized a cold bending technique called lamination bending to achieve its flat and uniform appearance, while also reducing energy and cost. Photo courtesy of Sedak.

One of the world's most notable bent-glass structures, the renovated Gare de Strasbourg in France by Arbour's former firm Seele, employs a new variant of cold bending called lamination bending, in which layers of heat-strengthened float glass are bonded with a DuPont SentryGlas ionoplast interlayer in the vacuum of a pressurized autoclave. “The level of heat in an autoclave is much less than you would have in a tempering oven,” Arbour says, “so it doesn't actually soften the glass in any way. In this case, you have that kind of sandwich, two pieces of glass with a material in between, and you cinch it onto a curved steel framework…you put it in the autoclave, you bond it together and take it out, you can take that piece of glass off the framework, and it'll spring back a little bit, but it won't take its flat shape, because the bonding between the two layers is actually taking the stress of the glass wanting to spring back into flatness.” Avoiding reheating the glass prevents optical distortion; pre-stressing the glass in the industrial process rather than on the building site requires less force to achieve curvature; handrails, metal elements, and seals can be bonded into the glass at the factory, simplifying on-site procedures. Most of the glass in the Strasbourg station was formed with this method, which saves energy and cost over hot bending while yielding a highly flat and uniform appearance.

Seele's glass-fabrication unit, Sedak, pioneered the lamination-bending approach, first demonstrated on a curved-glass bridge (winner of the Innovationspreis Architektur und Glas at Düsseldorf's Glasstec exhibition in 2008), then at Strasbourg. It is currently being used for the large façade glass panels and roof canopies of Foster + Partners' new Apple campus in Cupertino, California, where some 30,000 square meters of curved glass—the largest pieces in the world, about 15 m by 3.2 m (49 ft by 10 ft)—will give employees unprecedented views both outside the vast torus-shaped mother ship and into its internal park. “The size of the pieces is extraordinary,” comments Arbour. “The innovative aspect of cold bending is interesting, and not being done anywhere else in the world. The sheer scale of the project is unique.”

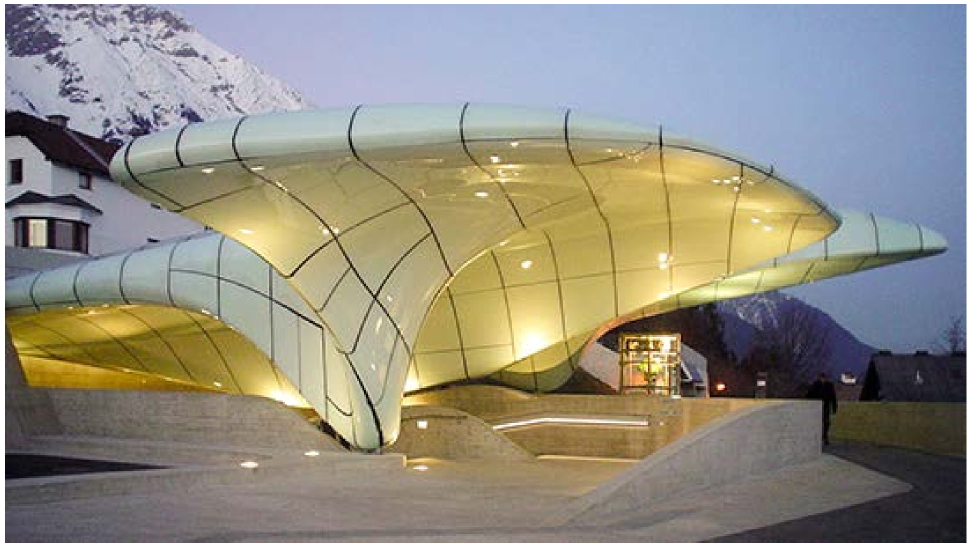
Ulrich Theisen, director of Sedak GmbH & Co. KG in Gersthofen, points out that large radii are easier to achieve with cold bending than smaller ones and that the only climatic limitation on the lamination-bending method is that the internal film may weaken if used in hot regions. Lamination bending, says Theisen, is also used for the five 8.1-m-long panels of the atrium roof of the newly opened Aria Hotel in Budapest, the largest laminated curved IGUs in Europe; the hotel repurposes an 1870s-vintage bank building. In Frankfurt, the Städel Museum sports circular roof lights made of Sedak's “only slightly lamination-bent” spherical glass, curved in all directions. However, not all geometries are a good match for lamination bending, Theisen says; right angles and diamond shapes are “all reserved for hot-bent glass.”

The Aria Hotel in Budapest features the largest laminated, curved IGUs in Europe. Photo courtesy of Sedak.

Full-Featured with Curves

Curvature is only one of many properties required in contemporary glass, including low-emissivity coatings, energy-conserving frit, and interactive electronics, allowing combinations that are innovative in both form and function. “There are some coatings that can be applied to flat glass and then bent into shape without disrupting the performance of the coating,” says Arbour. Although fritting applied through either silkscreening or digital printing methods is easier on flat glass, curved glass can also accept frit, Arbour points out; curvature is not incompatible with any of these features, and post-temperable coatings can be preferable in buildings that include both curved and flat glass, so that appearance is uniform. London's Canary Wharf, he says, includes several good examples of such a combination (the best-known being Rafael Viñoly's 20 Fenchurch Street, the “Walkie-Talkie” or “Walkie-Scorchie” whose curvature famously focused sunlight to melt a car—a newly recognized risk of concave curves). Theisen adds that Sedak is studying the possibility of LED displays on lamination-bent pieces; as for “electrical switchable glass, I would say no at the moment,” but the future may hold “more intelligent uses for the glass, where you incorporate things into the glass as an advertising screen [or] big TV screen.”

Advanced three-dimensional geometries from parametricist architects like Zaha Hadid and Patrik Schumacher may involve bending along multiple axes rather than a cylindrical bend with a single radius; these complex glass units, Arbour reports, are generally heat-bent. The double-curved glass of Hadid's Nordpark railway stations in Innsbruck, Austria, inspired by glacier formations and “floating” above concrete plinths, used a combination of thermoforming and computer-numerical-controlled (CNC) milling, with panels developed by Bollinger & Grohmann and manufacturer Pagitz Metalltechnik, made in China. “The more complicated it gets,” Arbour observes, “the more difficult it gets to make it precise and have the joints be straight and uniform. So there are limits to what you can do; it's not inherently a plastic material, not like concrete that you can pour into a shape. You have to take it in its brittle form and find a way to put it into a different shape.”



Zaha Hadid's Nordpark Railway Stations used heat-bending techniques to achieve double curvatures.

Though glass technology is continually advancing, commentators caution that the physics of glass poses certain constraints that designers need to respect, particularly as energy-performance concerns and codes come into conflict with the material's thermal properties. Prescriptive energy codes, Arbour notes, if followed precisely, would call for no more than 30 percent glass in a building's exterior. "There's a whole gamut of other problems that come into play," he comments. A building like Bohlin Cywinski Jackson's Apple Cube on Fifth Avenue represents "a problem waiting to be solved," driving innovation through the desire to maximize the purity of an all-glass structure, but he does not expect this model to become a norm in construction. In trends toward larger pieces of bent glass, he continues, the design side is driving the technologies rather than capitalizing on technological breakthroughs; this process is inherently unpredictable. With the current prominence of unprecedented glass forms, Arbour believes, architects may be approaching a historic point, "achieving the all-glass building," and he does not know how long this obsession will last.

It was Paul Scheerbart's singular obsession, however. Though design trends may eventually swing back to rank thermal or cost considerations above optical ones, it's not hard to agree with the author of Glasarchitektur that people will always seek out the wonders of forms no other material can assume.

About the Author:

Bill Millard writes about the built environment and its relations to culture, health, and the natural world. His writing has appeared in Oculus, eOculus, the Architect's Newspaper, Icon, the LEAF Review, Annals of Emergency Medicine, Architect, Architectural Record, the RIBA Journal, Content (OMA/R. Koolhaas et al., eds.; Köln: Taschen, 2004), Metals in Construction, Architectural Lighting, and Postmodern Culture. Millard has a doctorate in English and American literature from Rutgers University, and his undergraduate work was at Amherst College. He is the former editor of Columbia University's interdisciplinary research magazine 21stC. Millard is currently working on a book with research support from the Graham Foundation for Advanced Studies in the Fine Arts titled The Vertical and Horizontal Americas: The Built Environment, Cultural Formations, and the Post-Automotive Era. He lives in New York's East Village.