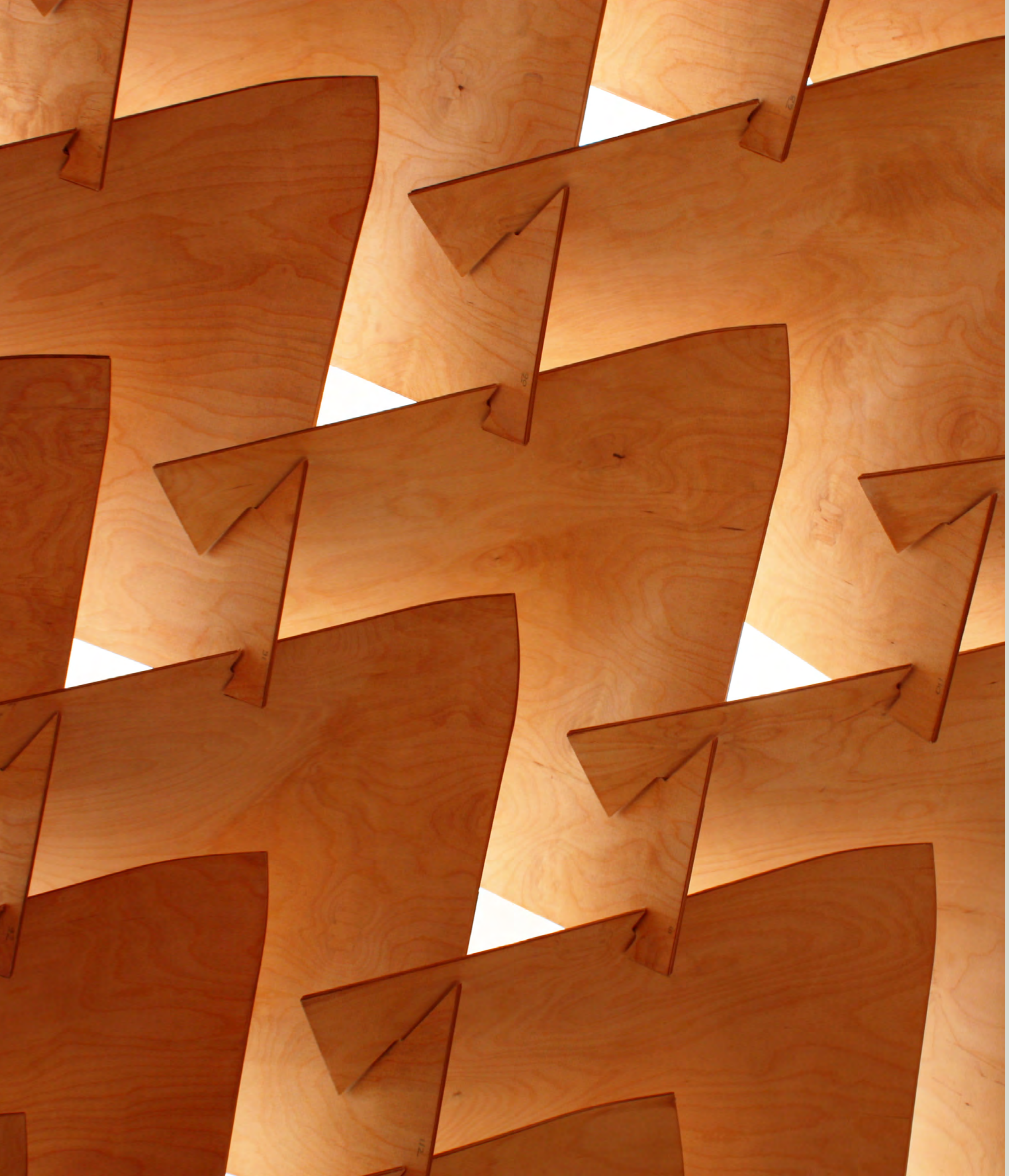


1

Manipulating Sheet

1.1 Slumping / 1.2 Thermoforming / 1.3 Explosive Forming / 1.4 Bending Plies / 1.5 Stamping 1.6 Hydroforming / 1.7 Spinning

Included in this section are processes that deform sheets of different media. All are previously manufactured sheet goods (e.g. plastic sheets, glass panes, or metal blanks) and are transformed into another shape. Transformations happen with added heat, pressure, force, or a combination of any of these. Because these processes start with a flat sheet, the final manufactured components will be limited in how far the material can be moved out of its original plane without tearing or incurring other damage.

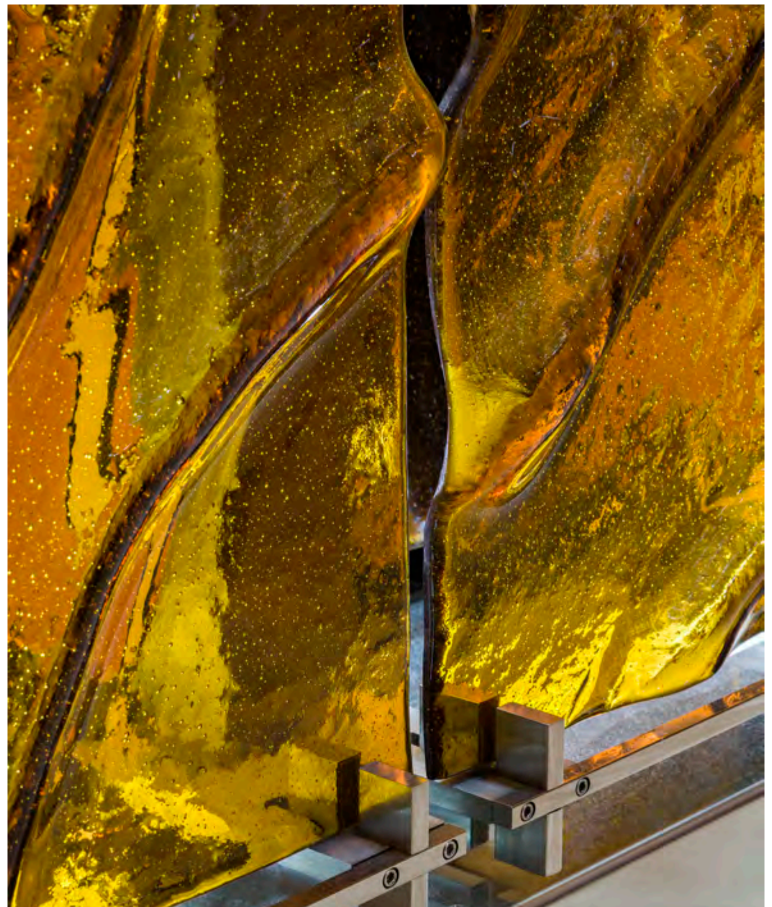
For manufacturing processes in this section there is a wide range of equipment, tooling costs, and facilities. Some processes, such as slumping glass and clay (Chapter 1.1), require no special equipment to deform the materials other than kilns. Tooling costs are minimal and molds can be made from refractory plaster for glass and canvas, or newspaper for clay. Other processes such as stamping (Chapter 1.5) and hydroforming (Chapter 1.6) require large presses and expensive dies made from tool-hardened steel. Meanwhile explosive forming (Chapter 1.3) requires inexpensive tools made from fiber-reinforced plastic (FRP) or concrete, but as a result of the large component sizes associated with the process, it often requires cranes for moving pieces and a remote worksite for detonations.

For all of these processes, the surface area of the components will be significantly larger than their cross-sectional thickness. In most cases the material deformation strengthens the material compared with its strength in its original sheet form. As the sheet deforms over the mold it can thin in some areas, causing tears or holes to the medium. Tools should have a small radius at entry corners to help ease the material flow around the tool, and draw angles are often required so that the component can be removed from the tool without damage.

4 Laurel Porcari, architectural art glass in *The Beacon*, a private dining room in *L'Auberge Casino and Hotel*, Baton Rouge, Louisiana. Made with fused art glass, slumped on a plaster mold and a custom stainless steel armature

For manufacturing slumped clay, molds can be made from steel, bisque-fired clay, plaster, wood, wood products, or Styrofoam. For prototypes, almost any material can be used, including draped canvas and wadded newspaper. For manufacturing slumped clay, steel is rarely used; although it is durable, it is the most expensive mold material, and production runs for slumping clay are often small. Generally, bisque-fired clay and plaster molds are the best for clay slumping, as those tooling materials absorb water from the clay, thereby decreasing the drying time necessary to stiffen the clay. This decreases the manufacturer's production time. Typically molds for glass slumping are more expensive than those of clay slumping, because they need to withstand the high temperatures of the glass kiln.

The molds for slumping are open and may be partial or full. A partial mold does not fully support the slumping medium during the manufacturing process. Instead, the medium is allowed to deform under gravity into a natural catenary curve. Partial molds depend on a combination of time, self-weight, and material viscosity to determine the depth of the drape. Partial molds work better with glass than clay, because glass will behave consistently at particular temperatures. For example, curved car windshields can be slumped using a partial ring mold, which only supports the glass along its edges. Within these parameters, the glass can be slumped to particular curves at a high tolerance.



5 Close-up of the glass

6 Laurel Porcari shaping the plaster mold to be used in the kiln

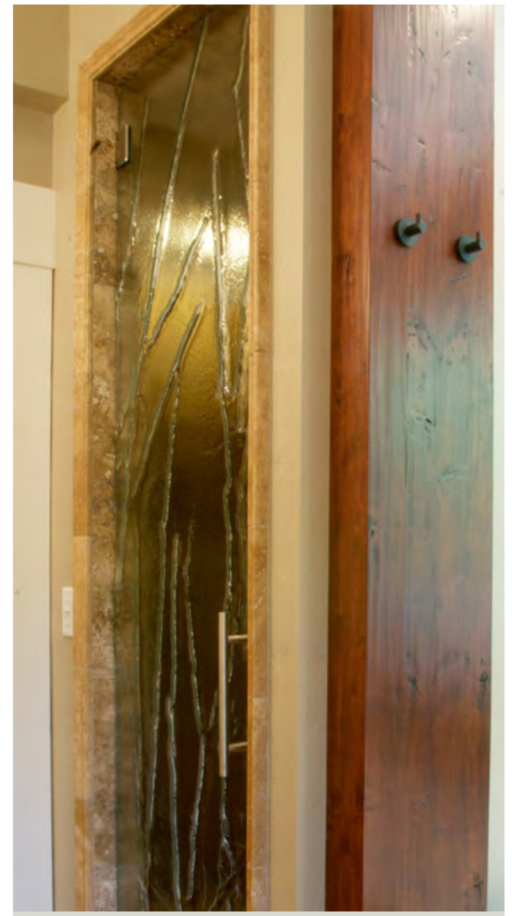
7 Slumped glass pieces and their molds

Glass slumping is best done in a partial mold when an architect desires visual clarity, as both sides are exposed to heat, giving the glass a flame polish.

In a full mold, the slumping medium deforms until it is in complete contact with the mold's surface. The mold's surface will directly transfer to the face of the slumped medium; therefore care must be taken to properly prepare the mold surface. Full molds can be symmetrical or asymmetrical, and either male or female. **[11]** If the full mold is a female mold, then ventilation holes must be added to avoid trapping air as the slumping medium fills the mold. **[12]** Slumping molds can be fairly intricate; however, the more intricate the mold the more difficult it is to slump the material. If the mold is too intricate, it can place stress on the medium as the medium shrinks, resulting in cracks. To avoid cracking, intricate molds should incorporate expansion joints, or be made from a flexible medium such as sand. **[13]**

Steel ring or partial molds are often fabricated by hand, but full, more complex tooling may be machined by CNC millers or spark or wire EDMs. Molds such as clay, plaster, or concrete are most often cast against hand-made or CNC-milled molds, but can also be made directly by CNC milling, or by hand pressing or other build-up methods. Wood molds can be fabricated by hand or CNC mills, and foam molds can be made by hand, CNC mill, or CNC hot-wire cutting.

8 CNC-milled pattern



10 The resulting slumped glass panel

9 Sand bed and kiln. The pattern is pressed into the sand bed, deforming the sand into the shape of the pattern. The sheet of glass is carefully placed onto the sand, and then the kiln is closed for heating

SLUMPING: GLASS

EXTERIOR GLASS PANELS
GORES GROUP HEADQUARTERS

Belzberg Architects

Los Angeles, California

Belzberg Architects was commissioned to design and to product construction documents for the renovation, addition, and new exterior skin of an existing 1960s Los Angeles office building. The project's original client was a law firm; however, the Gores Group bought the building after the building permit had been obtained and construction begun. In the interest of continuing to work on the project, Belzberg Architects contacted Alec Gores—founder, chairman, and chief executive officer of the Gores Group—to show him designs and mock-ups for the exterior glazing system. The new owner required some changes, but most of the original design of the building's exterior remained. The addition is a separate volume from the original building, and a bridge

14
Gores Group Headquarters by Belzberg Architects, Los Angeles, California. Wilshire Boulevard façade

15
Façade detail

MATERIAL CONSIDERATIONS + DESIGN PARAMETERS

Bent plywood is a composite material, one in which the adhesive and the veneers work together. The specific adhesive used depends on the required strength, tightness of curve, exposure to moisture, and desired cycle times. If manufactured by a craftsperson, white or yellow wood glues may be used; however, cycle times are long and creep may be an issue for tight curves. For components that are exposed to moisture or have tight curves, urea formaldehyde glue is best, though difficult to work with. Most contract manufacturers will use synthetic resins that are activated by heat-induction or radio waves, and pressure. Generally, heat-induction has a longer cycle time than radio frequency, but is better suited for complex parts as it is more precise and results in less distortion. After the blank is removed from the press it cools, and the adhesive continues to cure.

This chapter focuses on two different ply media—wood sheets and post-formable plywood. Wood sheets include individual sheets of wood veneers, thin plywood sheets, or bendy plywoods (e.g. Wacky Woods). With these, the wood sheets are laminated together with a wet adhesive, and are placed in the press until the adhesive cures. Post-formable plywood is a proprietary plywood that uses temperature change to loosen and set the adhesive between the layers of wood.

WOOD SHEETS

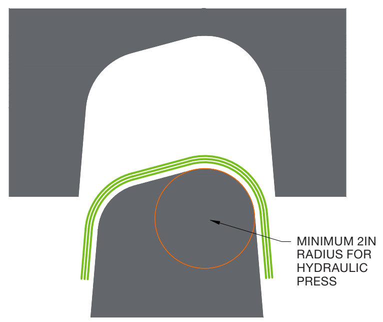
Typical wood veneers for bending plywood are Douglas fir, maple, or birch, but they can include any wood species, bendable plywood (less than 0.12in/3mm thick), or bendy plywood. If the design allows, most manufacturers will use inexpensive woods (e.g. fir or birch) or plywoods for the inner plies, while reserving the more expensive or decorative wood veneers (e.g. quartersawn mahogany or lacewood) for the face veneers. The inner layers can be in any thickness, as long as they can form the desired curve. The face veneers should be sanded prior to pressing, reducing the need for post-production sanding, which can be difficult on the curved surfaces of the bent plywood.

Wood veneers are cut thin enough for the desired curve and allowable springback, but thick enough to reduce labor costs and set-up time. Typically, the wood sheets are laminated dry, as the adhesive's moisture is enough to soften them for a little more flexibility. If the desired curve is too great or the wood sheets too thick, the sheets may require additional moisture for added flexibility, from steam or water soaks. This should be avoided, though, because added moisture can thin the glue and cause delamination with some adhesives, such as yellow wood glue.

In layups with wood veneers, the grain direction of the wood plies may be laid parallel or perpendicular to one another. If the plies' grains are parallel, then the bent plywood is called a lamination. It will act in a similar way to solid wood, expanding and contracting along the grain width with changes in moisture. If the plies' grains are perpendicular, the bent plywood is called veneering. In veneering, the changing grain direction of the plies provides stability in changing moisture conditions.

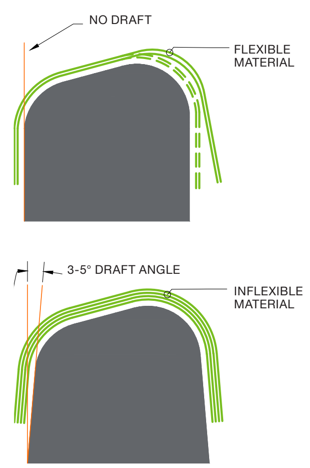
CURVE RADII

The minimum curve radius for contract manufacturers using a hydraulic press is 2in (50mm). The curve radius depends on the thickness of the veneers, the applied pressure, the moisture content of the wood, and the adhesive used. If made by a craftsperson in a workshop, you should expect a 4in (100mm) minimum radius.



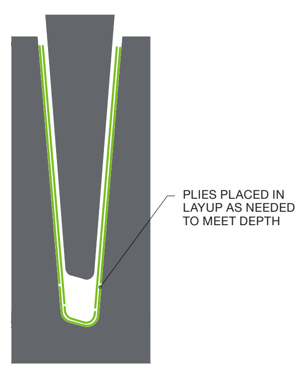
DRAFT ANGLES

If the bent plywood is flexible enough, draft angles are not required. If the bent plywood will be stiff, a draft angle of 3–5° is recommended.



DRAW DEPTH

There is no limit to the draw depth to this process, as the plies can be placed as needed, even vertically, into the tooling.

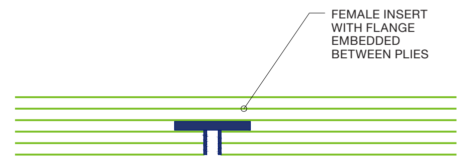


FINISH

The finish of the material depends on the finish of the face veneers rather than the mold surface. High-quality finishes should be done post-production.

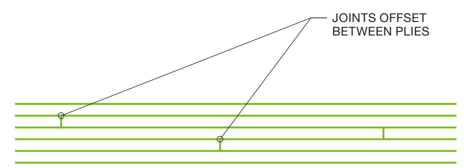
INSERTS

Fastener inserts may be added between the plywood layers for the final component assemblies. Plies should be cut to hide insert flanges as necessary.



JOINTS

Joints between wood plies within the layup must be offset from joints in the preceding and following layers. This will eliminate any material weakness at the joint.



PRODUCTION RUNS

Production run lengths will depend on the tooling media, the equipment, and the manufacturing facility. Workshops can produce prototypes and production runs of 2–50 units, with 2–25 being typical, using molds made from foam, cardboard, or plywood. Contract manufacturers can produce prototypes and production runs of up to 2,000 units.

PRODUCTION SPEED

Cycle times can be long. If manufactured in workshops, the time in the press may range from 4–12 hours, depending on the size of the piece, the number of plies, and the adhesive used. In contract manufacturing technologies such as heat-induction or radio waves are used to speed up the adhesive curing; cycle times are typically under 20 minutes per layup. Post-production CNC trimming may take an additional 3–10 minutes per piece depending on the cutting path.

SHRINKING

Unless moisture is added to the plies prior to bending, there is very little shrinking with this process.

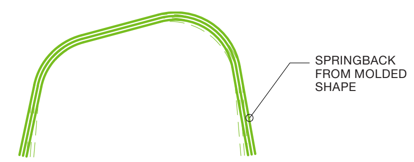
SIZE LIMITS

There are almost no size limits when bending plywood. Boats, airplanes, and furniture have all been manufactured by bending or molding plywood. The component size will be limited by handling and the available equipment, such as the size limits of the hydraulic press.

SPRINGBACK

Springback is normal in bending plywood, as the layers try to straighten against the curve. Springback of 0.06–0.12in (1.5–3mm) is normal. The amount of springback will depend on the thickness of the laminate, the type of plies, the amount of curve, and the type of glue. For example, yellow wood glue typically has more springback than urea glue. Generally, the thinner the laminates and the more plies, the less springback.

To counter springback, manufacturers will bend the plywood slightly tighter than desired, so that with springback the component will still meet design specifications.



TOLERANCES

Shape and curvature tolerances may be difficult to predict as a result of springback. If tolerances are an issue, prototypes should be made to predict the springback, or thinner veneers can be used. With CNC post-production trimming, tight dimensional tolerances can be maintained.

TOOL COMPLEXITY

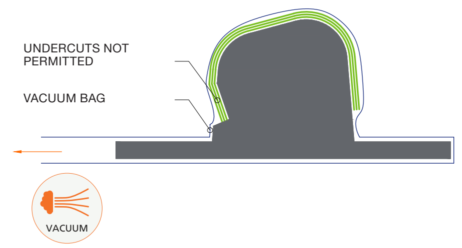
Tools are simple, almost rudimentary. Tools can be fabricated by CNC mills, routers, wire cutters, or by hand.

TOOLING COSTS

Tooling costs for this process are quite low. A large, single-bend, closed, wood mold suitable for mid-volume production runs can range from $1,000–5,000.

UNDERCUTS

Typically when manufacturing, undercuts are not permissible as an undercut will keep a full mold from closing are a vacuum bag from applying ample pressure. For making prototypes with clamps or jigs, a undercut is permissible.

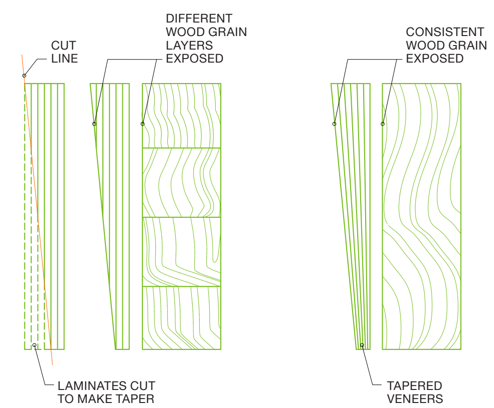


VENTS

Vents are not required as the press moves slowly and air can escape out of the sides of the mold.

WALL THICKNESS

Wall thicknesses typically vary from 0.12–1in (3–25mm). Typically, the wall thickness needs to be consistent for the entire component. If not, then the layers of wood sheets and adhesive will be visible and will negatively affect the component's finish face. If the layers are custom cut, then they can be cut into a tapered angle. This creates a layup with a varying thickness. This technique is much more expensive, and likely will only be done by highly skilled craftspeople.



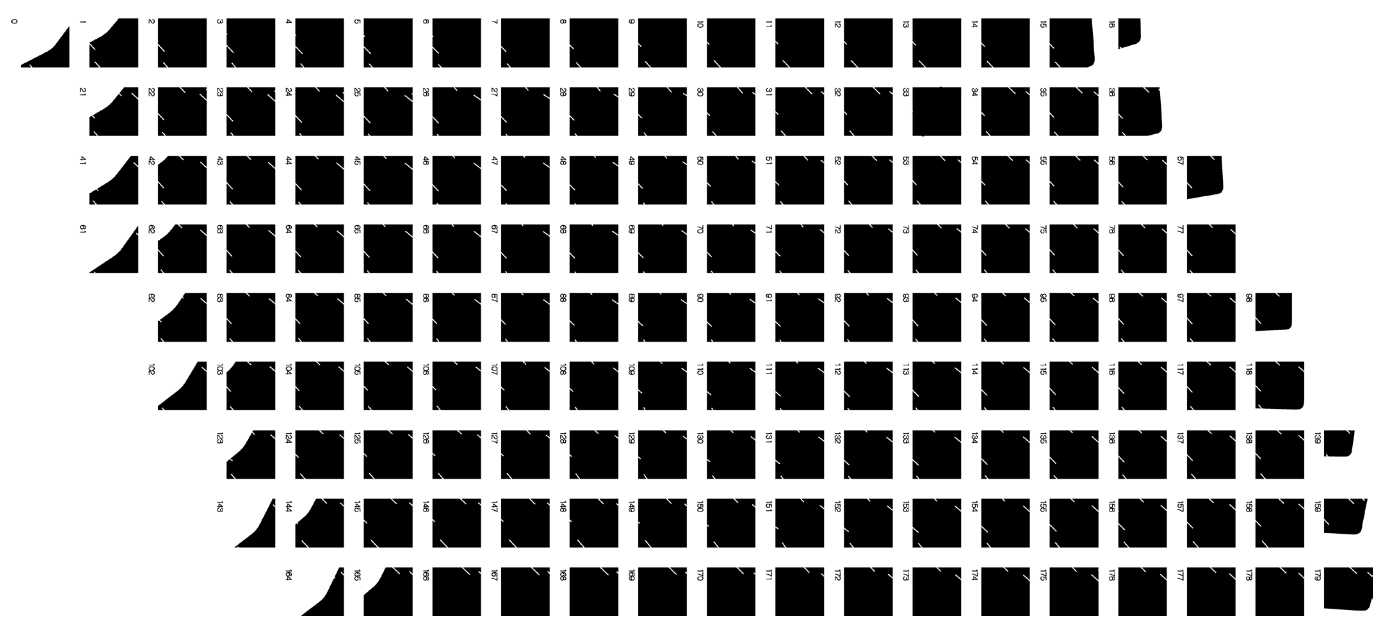
STRUCTURAL SKIN | DRAGON SKIN PAVILION

Emmi Keskisarja and Pekka Tynkkynen (EDGE), and Kristof Crolla and Sebastien Delarange (LEAD)

Shenzhen Pavilion, Hong Kong, and Bi-City Biennale of Urbanism/Architecture, Shenzhen

The Dragon Skin Pavilion was a temporary pavilion made for the 2012 Hong Kong and Shenzhen Bi-City Biennale of Urbanism/Architecture, and was located in the Shenzhen Pavilion of the Biennale. **[32, 42]** The Biennale occurs every two years, and architects apply to have projects accepted. It features architecture and art installations, and other exhibitors for the 2012 Biennale included Office for Metropolitan Architecture (OMA), Steven Holl, MVRDV, and Reiser + Umemoto. The pavilion's design was the result of a collaboration between Laboratory for Explorative Architecture & Design (LEAD), a young Hong Kong- and Antwerp-based architectural design and research practice founded by Belgian architect Kristof Crolla; and EDGE Research Lab at Tampere University of Technology (TUT). Founded in 2005, EDGE's goal is "to develop and dispose of funding for new research projects" for TUT.

The collaboration between LEAD and EDGE was initiated by Emmi Keskisarja, a PhD candidate at TUT. Keskisarja was researching potential intersections between digital design, digital fabrication, and the Finnish wood industry. As part of her work, Keskisarja invited Crolla to lead an eight-day architectural design workshop at TUT, titled Material Design and Digital Fabrication. In this workshop students worked with Grada and parametric modeling software to design a structure from post-formable plywood.



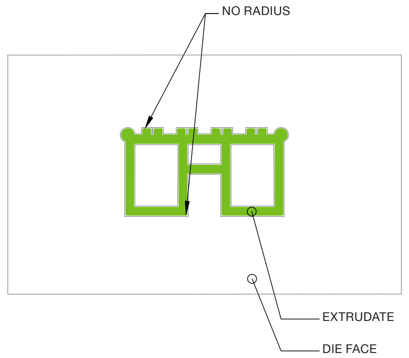
35 Cutting figures for CNC milling. All **163** panels and their joint locations

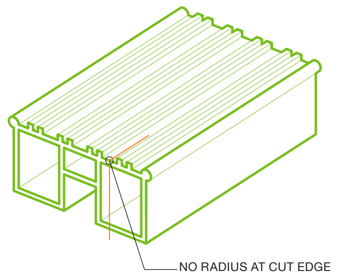
32
Dragon Skin Pavilion by Emmi Keskisarja and Pekka Tynkkynen (EDGE), and Kristof Crolla and Sebastien Delarange (LEAD), located in the Shenzhen Pavilion of the Hong Kong and Shenzhen Bi-City Biennale of Urbanism/Architecture. An exterior view of the Dragon Skin Pavilion in the Shenzhen Pavilion in Kowloon Park

42
Panels interlock with one another through slotted connections

CORNER RADII

Corner radii are not required.





FINISH

The surface formed by the die is smooth, with long mill lines running the length of the component. Post-production finishing can be done to achieve satin, grit, or polished surfaces.

HOLLOW

Most extruded aluminum components are hollow, as material costs are high; however solid components can be extruded.

JOINING

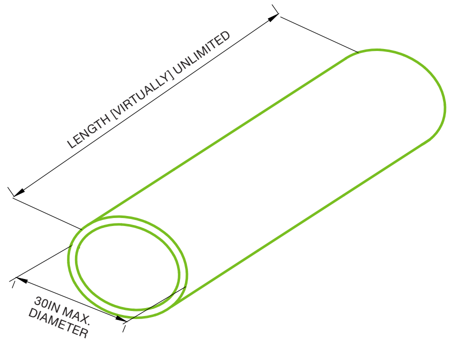
Units cannot be joined during the extrusion process. Any joining of components is done post-production, and is often mechanical, as aluminum is difficult to weld.

SHAPES

Extruded shapes have the same profile along their length. Extruded aluminum can be simple or complex, as the material can pick up fine details.

SIZE LIMITS

Extruded aluminum components are limited to 30in (120mm) in diameter.

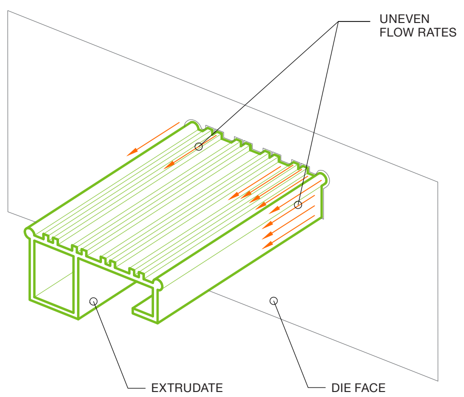


SURFACE DESIGNS

This process accommodates fine textures and designs that run the length of the component. It does not accommodate in-line patterns or textures.

SYMMETRY

Generally, symmetrical shapes are easier to extrude. Asymmetric shapes will affect the consistency of metal flow through the die. This can cause cracks and rips in the extruded component. The die can be designed to make the flow more consistent, which will increase costs.



TOOLING COMPLEXITY

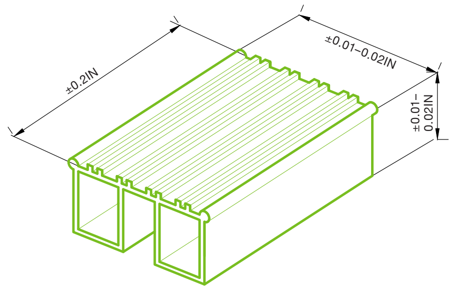
Tools are simple for this process and have no moving parts.

TOOLING COSTS

Tooling costs are moderate, due to the amount of steel necessary to resist the pressures of extrusion. Aluminum-extruding dies often start at $10,000, and the cost increases with complexity.

TOLERANCES

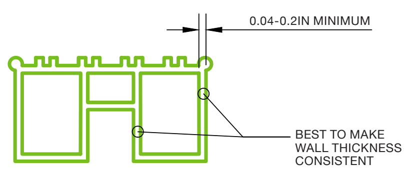
Profiles are commonly held to 0.01in–0.02in (0.25–0.5mm), but tighter tolerances are possible. Cut tolerances are more difficult to maintain than extruded tolerances, and can be 0.2in (5mm).



WALL THICKNESS

It is best to design profiles with a consistent wall thickness, or transitions between one thickness and another. Profiles with an inconsistent wall thickness can be extruded, but there is increased difficulty in machine operation and die design. Metal flows slower through thicker-wall areas than thinner-wall areas, causing cracks and rips in the extruded component. This can be partially fixed by the die's design, but this will increase costs.

Minimum wall thicknesses can range from 0.04–0.2in (1–5mm), depending on the size of the component, the cross-sectional area, and the particular aluminum alloy.



METAL (ALUMINUM)

CURTAIN | OMS STAGE

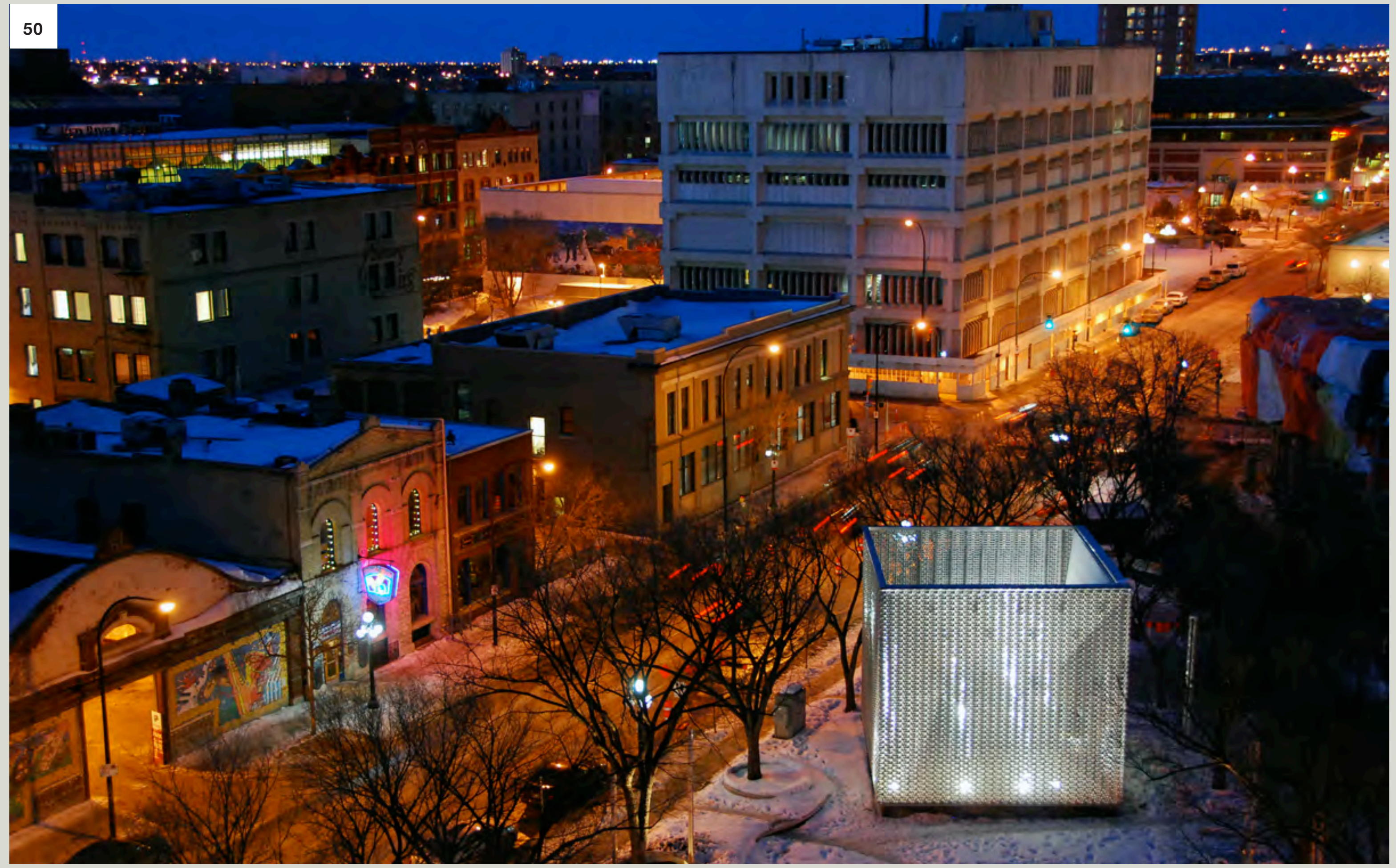
5468796 Architecture

Winnipeg, Canada

The city of Winnipeg held an open competition to design a bandshell for Old Market Square (OMS) in Winnipeg's Historic Exchange District. **[53]** The new structure was to replace an original bandshell, which was used only fifteen times per year. According to the architect's website, the design of the OMS Stage was a response to the traditional bandshell that looks forlorn throughout Canadian long winters. 5468796 Architecture's winning submission was for a building that would serve as a public stage, with a private stage on the second level, a pavilion, a projection screen, and a beacon, allowing it to be used year round. The building is a 28ft (8.5m) cube. The private stage is accessed from an internal concrete stair, and is open to the sky. **[50, 51, 52]** The building is unconditioned, but fully wired with sound, lights, and interior projection.

5468796 designed the OMS Stage to be draped with a flexible curtain, made from custom-manufactured aluminum extrusions. Similar to chain

53
OMS Stage by 5468796 Architecture in Winnipeg, Canada, at night



50
Aerial view of OMS Stage and Old Market Square

THERMOPLASTIC

POLLI-BRICK | ECOARK

Miniwiz

Taipei, Taiwan

44
EcoARK by Miniwiz in Taipei, Taiwan. Aerial view. This building has over **480,000** custom plastic, blow-molded POLLI-Bricks

45
Corner detail of building

51
EcoARK night view, with LEDs inside some of the POLLI-Bricks

The EcoARK is a large pavilion that hosted fashion shows and provided exhibition space for the 2010 Taipei International Flora Exposition, which ran from November 2010 to April 2011. Designed by Miniwiz, the EcoARK has 21,500ft^2 (2,000m^2) of floor area and is nine stories tall. **[44, 45]** It was engineered to withstand earthquakes and typhoons, common to Taipei. In keeping with the inherent nature theme of the exposition, Miniwiz designed the building to be as environmental and sustainable as possible. The building is cooled without air-conditioning and is carbon neutral.

Miniwiz designed the EcoARK's exterior wall with a custom plastic blow-molded bottle that interlocks with one another. **[46, 47]** The bottles are filled with air, for insulation, but can also be filled with water or sand for thermal mass. The building is about half the weight of a conventional building, which in turn reduces the amount of structure and foundations required. According to a *Wall Street Journal* article about the EcoARK, the building is the least costly of its size ever made. Building construction cost $250/m^2.

Far Eastern Group, one of the largest plastic producers in Taiwan, commissioned the EcoARK and donated it to the city. Douglas Hsu, group chairman of the Far Eastern Group, supported the project so his company's bottle waste could be upcycled. The EcoARKs bottles are made from recycled polyethylene terephthalate polymer (PET) bottles. PET is the plastic typically found in disposable soft drink, water, and juice bottles. Taiwan has a high recycling rate, with 90,000 tons (more than 8 million kilograms) of plastic being recycled every year, so it seemed appropriate for Miniwiz to use this material in its design. In the end, the EcoARK upcycled 1.5 million PET bottles into 480,000 new, plastic blow-molded bottles. **[48]**

Unlike other case studies in this book, the custom manufactured components were not limited to just the EcoARK. Miniwiz has since developed its blow-molded bottles into a commercially available building product, named the POLLI-Brick. According to the British Broadcasting Corporation (BBC), Miniwiz has gotten requests to use the POLLI-Brick for gymnasiums, military bunkers, and other portable applications. Filled with air, the POLLI-Brick performs almost the same as a triple-layered, vacuumed glass unit, but at a sixth of the cost. It can withstand 68lb/ft^2 (3,255 Pa) of lateral wind force with a fifth of the material weight.

Currently, POLLI-Brick comes in translucent, semi-translucent, and white, but custom colors can be manufactured. POLLI-Bricks are available in three different sizes: 6,000ml, 690ml, and 400ml (203fl oz, 23.3fl oz, and 13.5fl oz), with varying heights of 12in, 7in, and 4.6in (30.8cm, 18cm, and 11.8cm) respectively. The largest size of POLLI-Brick can be used for interior or exterior applications, while the two smaller sizes can only be used for interior applications. POLLI-Bricks are self-extinguishing, fire retardant, and flame retardant, and they meet standards set by ASTM, AAMA, and UL.

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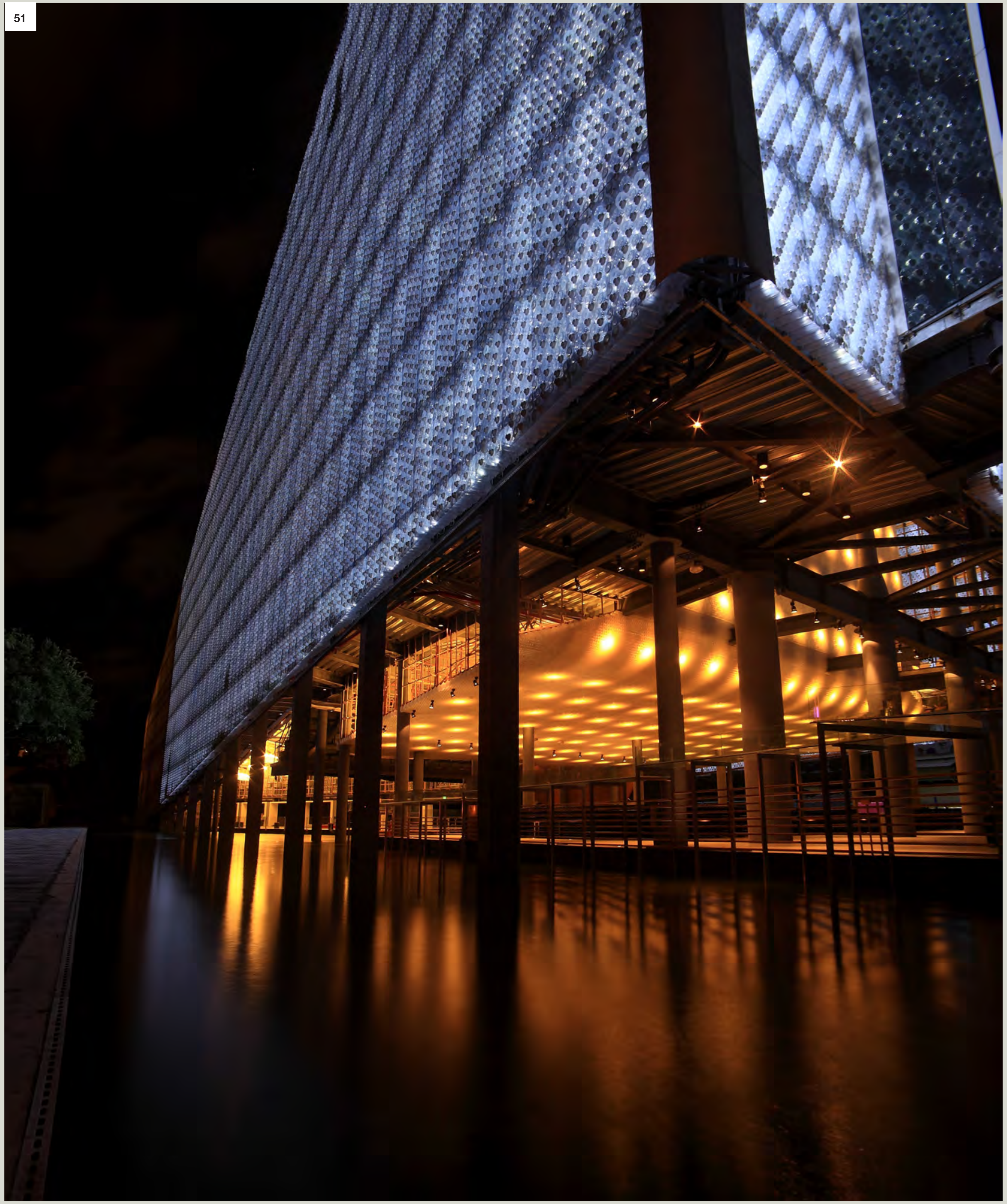

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