PAPER

Optimized Design and Fabrication of Economical Double Curved Metal Façades

CHRISTIAN DAVILA-PERALTA
University of Arizona

SUSANNAH DICKINSON
University of Arizona

JUSTIN HYATT
University of Arizona

SAMUEL OWEN
University of Arizona

Keywords: complex curvature, digital methodologies, fabrication, facades, shade structures

While there is an increased desire for complex geometry in the built environment, affordable fabrication processes are still in their infancy.[1] Economical workarounds have historically existed including the use of developable surfaces (Walt Disney Concert Hall, Los Angeles), rationalization techniques (Mercedes Benz Museum, Stuttgart) and cold bending techniques (Experience Music Project, Seattle). More recently the Dongdaemun Design Park (DDP), designed by Zaha Hadid Architects in Seoul, South Korea utilized a multi stretch forming machine, with two mating dies and high pressure.[2] At the University of Arizona researchers have developed an economical technology to manufacture precision, compound-curved aluminum metal sheets for satellite communication dishes, answering a need for increased high speed internet demands. This developed technology has been recently expanded and adapted for economical building façades, in collaboration with the architecture department, giving an opportunity to connect space technology with the built environment, natural forms and systems. This paper disseminates the associated optimized design process, manufacture and installation of a full-scale demonstration project of this technology on the aforementioned college campus.

THE HISTORY OF FORMING CURVED METAL

Early industrial efforts at forming metal sheets into compound curves were motivated by the growing automobile industry in the 20th century. Curved fenders and other body parts were formed manually using an English wheel. Eventually as production volumes increased, car manufacturers built large stamping machines that used machined die to form identical shapes. The development of metal aircraft also drove demand for curved metal panels. The frustum-shaped fuselage was common because of its lack of compound curves. “They are inexpensive to produce because they can be made from folded sheet metal riveted to frames, which produces a light and stiff structure. It is a drawback that they generate far more drag than tadpole fuselages”.[3] Eventually large stretch forming machines were developed that grip a sheet of aluminum on two ends and move it downwards with hydraulics to stretch it across a mold. The remaining border is then trimmed leaving the curved panel. This process is still used to form compound curved metal aircraft panels, but it requires a unique mold that can withstand high force for each desired panel shape.

Curved metal has been used in architecture for decades. Initially, metal sheets were rolled in one direction forming cylindrical curves. Frank Gehry pioneered the use of compound curves in building skins, designing works such as the Walt Disney Concert Hall and the Museum of Pop Culture, (originally the Experience Music Project, EMP), in Seattle. These used developable surface segments that approximated compound curves. Thin, flat metal skin was wrapped around and attached to curved structural members and overlapped like shingles. Another approach is the use of cylindrical facets angled to approximate compound curves. These methods achieve a curved appearance in large structures at far distances.

The popularity of Gehry’s work has led to other projects and technological developments. Metalarchitecture.com reported on the growing importance of curves in architecture:

> “Architectural curves provide an aesthetic comfort and appeal ideal in many situations,” says Robert Widmer, marketing manager, Flex-Ability Concepts, Oklahoma City. “Architectural curves can be used very effectively in facilitating smoother and more natural traffic flow.” Bruce Congdon, general manager, Duraframe Solutions, Webster, N.Y., says to further improve building functionality, acoustic treatments can be integrated with curved surfaces, to control sound in auditoriums and theaters. [Also,] “Exterior curved framing can help control the way light enters a building, providing energy savings. Attractive curved surfaces and ceilings can dramatically enhance interior spaces and façades, contributing to increased foot traffic and business for retail and hospitality projects. The possibilities are endless” (Robins 2021).[4]

Freeform surfaces can be shaped to provide higher performance at an engineering level such as minimizing surface area to limit heat loss; self-shading; directing water, light, or sound; etc. They also give the opportunity at a spatial level to provide more

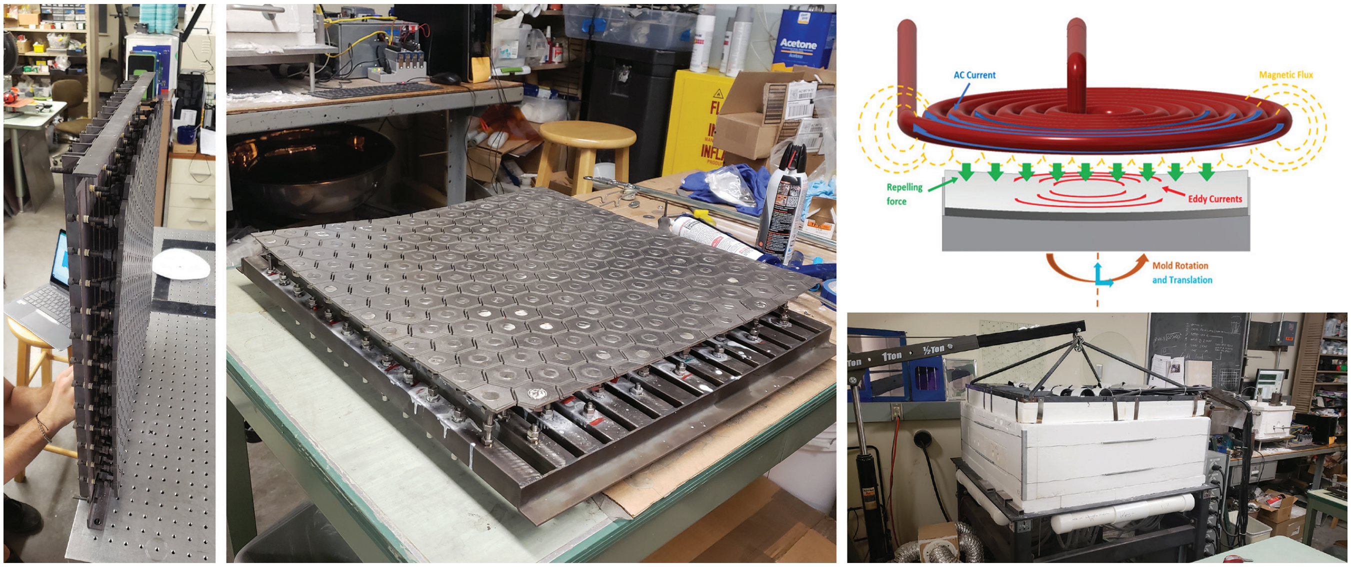

Figure 1. Images of the thermoforming process: adjustable mold and oven with diagram of the induction heating process. Images by authors

continuous forms that allow for more natural flows of air and human movement. “Geometrical complexity remains the precondition for efficient structures in architecture, and this simple paradigm can be observed in nature, beyond time-dependent stylistic and formal discourse”.[5]

As the popularity of curved metal architecture grows, its constructability is also improving. Numerical software facilitates curved designs and optical and aerodynamic analysis. Building Information Modeling (BIM) platforms enable communication of complex plans and part identification and tracking. Computer Numerical Controlled (CNC) benders economically produce curved support structures. Laser surveying integrates with BIM designs to facilitate complex installation. The last missing piece is economical fabrication of freeform curved panels.

Recent efforts have attempted to develop a viable method of fabricating custom curved panels including experimenting with a robot assisted English wheel[6], and adaptive base plate 3D printing. A notable example of a building using true compound curved panels is the Dongdaemun Design Park, which used a reconfigurable stretch forming mold to make thousands of unique panels.[7]

THE THERMOFORMING PROCESS

At the University of Arizona researchers have developed an economical technology to manufacture precision, compound-curved aluminum metal sheets for satellite communication dishes, answering a need for increased high speed internet demands.[8] These researchers recently collaborated with the architecture department to expand and adapt this technology for economical building façades. Metal sheets for radio reflectors are generally all concave or all convex and do not typically have taurus or “saddle” shapes. Also, the shape accuracy specifications are far stricter than those required for architecture. The original, developed system has been simplified to match architectural shape accuracy requirements and adapted to create freeform curves.

The fabrication process begins by heating a flat metal panel (blank). Raising the temperature of the blank significantly reduces the yield strength of the material, which allows the panel to be formed with less pressure than cold processes like stretch forming. This allows the reconfigurable mold to be less rugged and rigid. The high temperature process also decreases springback.[9] This heating can be done in a traditional convection/radiation oven. It can also be done by alternating electromagnetic fields to induce heat. The induction process performs a second function of applying contactless pressure on the sheet to be formed. High frequency alternating currents in a coil above the sheet create opposing currents in the metal sheet. This pair of opposing currents causes a repelling force between the coil and the blank that presses the sheet into conformance with the mold.

The singular, adaptable mold consists of a continuous array of segmented tiles, each of which can be positioned by an actuator. By adjusting these actuators, the shape of the mold can change. As this system is adaptable, multiple high-precision panels of different shapes can be formed without costly machining or retooling. This enables rapid, custom complex shaping of thin and lightweight panels that cannot be economically machined by existing fabrication methods. A freeform architectural skin was designed to demonstrate this fabrication method.[10]

INTENTIONALLY DIRECTING REFLECTIONS

While discussing this project, a university committee raised the concern of the curved surface dangerously focusing light. The incident of the Walkie-Talkie building at 20 Fenchurch Street,

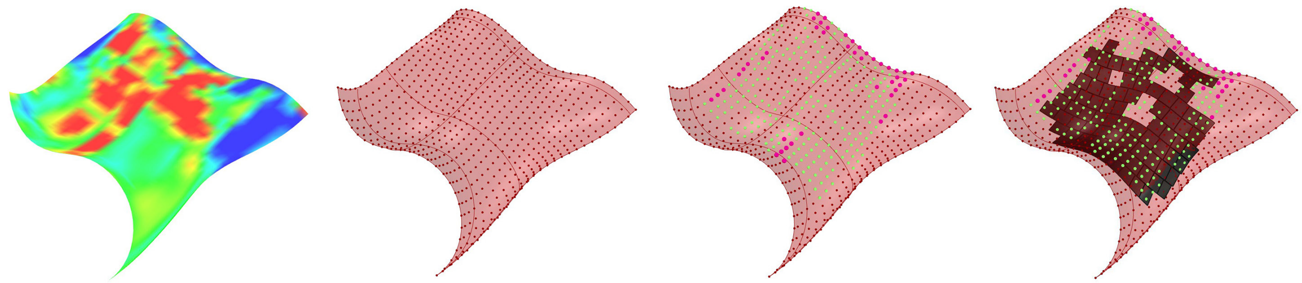

Figure 2. Digital process of the freeform surface designed to become part of a shade structure. Image by authors.

London melting car components is an infamous example of this risk.[11] The University of Arizona design team used optical ray tracing software to analyze reflected solar irradiance at different times of the day and year. These analyses allowed the team to preemptively avoid dangerous scenarios. Concentrated sunlight is also a risk for radio communication dishes and the team has performed extensive experiments and developed surface treatments to diffuse light and heat.[12] These chemical processes create a matte finish on the façade panels that scatter light evenly preventing dangerous concentrations.

DEMONSTRATION PROJECT DESIGN PROCESS

To demonstrate this process a complex curved shade structure was designed for a site on the university campus at an entrance to a facility, where people congregate, specifically one of the public entrances at Biosphere 2. There was an existing structural framework present, but no shading panels. This site seemed ideal as a skin could be attached with a minimal secondary structure, rather than having to build a primary structure. As it was completely exterior it also meant that there would be no issues with penetrations to existing building envelopes etc.

The panel size was determined by maximizing the existing adaptable mold, this was a square of 0.5 meters along its sides. The team is currently working on a larger mold (2 x 2 metres), but as it is still in production, they utilized the smaller, existing mold to expedite the fabrication and construction process.

The goal of the installation design was to develop a surface with optimally tight curvature without going below the minimum curvature constraints as defined by the fabrication technology. First, a surface was generated by sweeping a set of rail curves that were drawn to match the minimum radius of curvature. This surface was then divided into a grid of points and the minimum curvature radius was measured at each point. Using Rhino Grasshopper[13] plugins Galapagos[14] and Anemone[15], a script selected (at random) points that failed the radius constraints and moved them along their normal vectors by a set distance. The script then checked if the new surface contained fewer points that failed the radius constraints. If the new surface was an improvement, it was kept and iterated on again. If the new surface made no improvement, it was scrapped and a new set of points were selected to adjust on the previous surface. This process was repeated until every point on the surface matched the radius constraints or fell outside of the panelized region.

To panelize the compound curved surface, a script in Rhino Grasshopper was created which was based around offsets of contours, which accounted for the desired gaps between the panels. This was started from the most complex part of the surface to produce the most aesthetically pleasing edge curves. To complete the transverse panel edges, the contours were divided along their length and connected. As each contour was different this patterning was stepped across rows to appear random and to provide more tolerance during the fabrication process. The individual panels were exported as Standard Triangle Language files (STL) to the fabrication team.

PANEL FABRICATION

The fabrication team developed customized software to process the panel Computer-Aided Design (CAD) files to determine optimal parameters for the actuators of the adjustable mold. First the STL file for a single panel is loaded. Next the file is stripped down to the x,y,z coordinates of the point cloud data that make up the sampled panel surface. In order to minimize the adjustment needed in the mold actuators, the panel point cloud is rotated to as close to horizontal as possible by making the cloud's best fit plane the new x,y plane. The point coordinates are rotated using transformation matrices. The point cloud is then rotated around the z axis to align the clocking of the panel with the square mold boundary outline. Next numerical analysis generates the best-fit fifth order polynomial to describe the shape of the curved panel. The code then calculates the required height of each mold actuator by inputting the x,y coordinates of the actuator into the polynomial. Each actuator is then set to the respective optimal height. After the mold is set, its target shape is verified by measuring the shape of the mold surface. The team has developed multiple metrology methods including probing

Figure 3. Renderings of the freeform metal shade structure. Image by authors and Rachael Varin

Figure 4. Mock up of one row of panels thermoformed using the method described to the shape of the designed surface. Image by authors.

with a coordinate measuring machine (CMM)[16]and 3D scanning using fringe projection photogrammetry.[17] The measured mold shape is then compared to the theoretical panel shape and iterative corrections are made as needed. Once the mold shape is set, a flat panel is placed on it, and the panel is heated and pressed to conform to the shape of the mold. The shaped panel is then cooled and removed.

FAÇADE SUPPORT STRUCTURE AND PANEL MOUNTING PROCESS

A critical component of curved architectural features is structural support. The location of each mounting point for a freeform surface varies relative to straight structural members. In addition to undulating mounting locations, the angle of the surface changes requiring flexibility in the mounting hardware. For this project the shade structure is existing. The team designed an intermediary structure that connects to the existing truss and the façade panels. The intermediary structure consists of round tube members that follow the contours of the surface. CNC tube bending machines are available that can produce custom curved structural tubes. However, for economic reasons the team elected to build these contours using straight segments that are mitered using a CNC laser cutter and welded together. After the contoured intermediary structure is attached to the existing truss, the panels need to be mounted.

The team designed mounting brackets to attach to the panels. Each bracket is designed to clamp to a round structural tube. The bracket then has two threaded rods with swivel pads on the ends. These pads are bonded to the panel with adhesive. The swivel connection allows for the varying angles of the panels, and the threaded rods allow for adjustment of the position of the panel to align the surface.

FUTURE WORK AND CONCLUSIONS

Once the current project is completed, the team plans to place sensors above and below the panels to measure heat gain behind different panel finishes and distances. As this research progresses, there are several facets to explore. Improved (digital) methodology could be embedded in the marketing process. Currently this technology is ready for interior use and for use as a rain screen, shade, or breathable wall for parking structures, etc., but it is anticipated that it could also serve as a building envelope. The team plans to develop an inter-panel joint system that works with freeform curves.

ACKNOWLEDGEMENTS

The authors would like to thank Tech Launch Arizona for funding this research and Biosphere 2 for the site location. The success of this project is also a result of the work and ideas of Dr. Daewook Kim; student research assistants Joel Berkson, James Colby, Wyatt Ellis, Zack Hatfield, Naomi Dinh Bao Ngoc Nguyen, Alex St. Peter, Rachael Varin; and digital process consultation with Senior Lecturer Sheehan Wachter.

DISCLOSURE

Authors Justin Hyatt and Christian Davila-Peralta have financial interest in Paramium Technologies, a company that commercializes freeform metal shaping technology.

ENDNOTES

1. Sherif Abdelmohsen and Sherif Tarabishy. "Optimized design to robotic production: integrating multipoint forming and free form material deposition in the mass customization of double curved façades." International Journal of Parallel, Emergent and Distributed Systems 32, no. sup1 (2017): S180-S189.

2. Gang Lee and Seonwoo Kim. "Case study of mass customization of double-curved metal façade panels using a new hybrid sheet metal processing technique." Journal of Construction Engineering and Management 138, no. 11 (2012): 1322-1330.

3. Snorri Gudmundsson, *General Aviation Aircraft Design II The Anatomy of the Fuselage*. Elsevier, New York, NY 2014. Ch. 12 521-545.

4. Mark Robins. "Optimizing curved metal to enhance buildings." Metal Architecture. August 30, 2021 Retrieved October 20, 2021, from https://www.metalarchitecture.com/articles/optimizing-curved-metal-to-enhance-buildings.

5. Sigrid Adriaenssens, Fabio Gramazio, Matthias Kohler, Achim Menges et al. 2016. "Advances in Architectural Geometry 2016." vdf Hochschulverlag AG an der ETH Zürich. Accessed October 20, 2021. http://vdf.ch/advances-in-architectural-geometry-2016.html.

6. Gabriella Rossi, and Paul Nicholas. "Modelling a complex fabrication system: new design tools for doubly curved metal surfaces fabricated using the English Wheel." In proceedings of eCAADe 2018: Computing for a better tomorrow, pp. 811-820. 2018. Also see reference in Endnote #1

7. See reference in Endnote #2

8. Christian Davila-Peralta, Justin Hyatt, Zack Hatfield, Alex St Peter et al. "Electromagnetic Thermoforming to Manufacture Reflective Panels for Radio Telescopes and Downlinks." In 2021 IEEE Aerospace Conference (50100), pp. 1-15. IEEE, 2021.

9. Rohit Verma. "Effect of elevated temperature on mechanical behaviour and springback of aluminum alloy brazing sheets." Master's thesis, University of Waterloo, 2016.

10. Marc Swackhamer and Blair Sutterfield discuss the importance of adapatable molds in Architecture, throughout history and in their work with vacuum formed thermosplastics, specifically in "Breaking the Mold: Variable Vacuum Forming" in proceedings of ACADIA 2013: Adaptive Architecture, pp. 269-278, 2013

11. Jiajie Zhu, Wolfram Jahn, and Guillermo Rein. "Computer simulation of sunlight concentration due to façade shape: application to the 2013 Death Ray at Fenchurch Street, London." Journal of Building Performance Simulation 12, no. 4 (2019): 378-387.

12. Zack Hatfield, Christian Davila-Peralta, Alex St Peter, Joel Berkson et al. "Surface Treatment Regimes for Solar Scatter Control in Millimeter Wave Telescope Panels." In Optical Fabrication and Testing, pp. OW2B-5. Optical Society of America, 2021.

13. David Rutten. (2007). Initially released as Explicit History. Grasshopper, https://www.grasshopper3d.com/

14. David Rutten. (2010). Grasshopper, https://www.grasshopper3d.com/

15. Mateusz Zwierzyck. (2013). https://www.food4rhino.com/en/app/anemone

16. Zack Hatfield, Christian Davila-Peralta, Joel Berkson, Alex St Peter et al. "Adaptive Aluminum Thermoforming for Precision Millimeter Wave Telescope Panels." In Optical Fabrication and Testing, pp. OW2B-4. Optical Society of America, 2021.

17. Joel Berkson, Emily Rodriguez, Zack Hatfield, Alex St Peter et al. "Fringe Projection Metrology for Thermoformed Millimeter Wave Freeform Optical Elements." In Optical Fabrication and Testing, pp. JTu2B-2. Optical Society of America, 2021.