

Shading with Folded Surfaces

Designing with Material, Visual and Digital considerations

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Abstract. *This paper analyses a hybrid design approach; how physical and digital processes can inform each other in a multivalent design cycle. It describes the design of origami-inspired window shades, part of the Shaping Light project that explores how adjustable surface structures can modulate light levels and heat gain in response to the changing seasons. The screen uses sloped surfaces to diffuse light and create apertures that close when the screen is stretched and open when the screen is folded. The project complements digital methods for pattern proportioning and kinetic simulation with manual manipulation to generate 3D folding motifs and refine assemblies. Physical prototypes can shape digital refinement by revealing visual and structural characteristics of materials, along with joint and production considerations. Physical models for simulating sunny and cloudy daylighting conditions provide a direct connection between spatial configuration and visual effects. The paper concludes with guidelines for material-based digital-analog creation.*

Keywords. *Architectural design process; digital fabrication; shading devices; origami.*

INTRODUCTION

In approaching a design problem, it is important to find efficient and effective tools for each stage of the project. Each tool that reveals specific perspectives and stimulates different creative opportunities. In working towards using the elegance and efficiency of origami for architectural scale shading devices, we asked "What is best done digitally? and "What is more effectively done outside of the computer?" We are interested in how digital tools can most usefully and efficiently shape projects that focus on material characteristics. This paper describes how different tools and talents shaped the direction of an ongoing research project known as Shaping Light.

Geometric Development

The project has concentrated on finding 2D cutting and folding motifs that generate compelling light gradients, then looking for unexpected visual synergy that results when combining motifs into emergent 3D forms. Curved folds shape sheet material into sculptural surfaces that variably reflect incident light as gradients of brightness. While inflexible materials such as paper can only curl in one direction in any location, the curl's radius can vary continuously to create complex combinations of conic or cylindrical surfaces. Cutting and lifting part of a surface creates a distance between two parts of the sheet that can bounce backlighting to diffuse incoming sunlight. As cut edges do not give form to the surface, they may be freely shaped for aesthetic purposes.

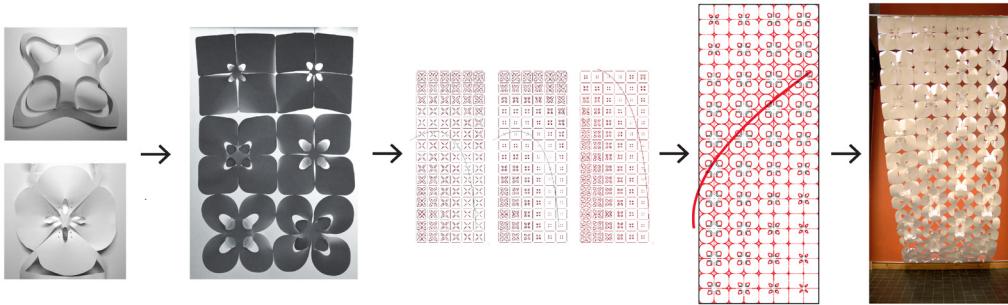


Figure 1
Flower petal motif was aggregated and varied to create the Shaping Light Veil installation.

The project began with pleating or cupping a paper slit into a pocket that bounces light. New forms have been most serendipitously found through quick paper trials, cut and scored with a hand-held knife over soft pencil lines. We created variations of a flower petal-like pocket, studying how tessellating curved folds in could generate compelling 3D patterns. In a precursor to the sun-screens, square to round variations of this petal motif ripple through a gridded 6' x 15' Shaping Light Veil installation cut from a roll of cardstock. This installation showed that it is invaluable to cycle between physical manipulation, lighting tests and digital modeling. Working for too long on the computer modeling without physical object manipulation made it difficult to understand the 3D form that would be generated from a 2D cutting pattern.

It was particularly important to have physical feedback when enlarging artifact dimensions. Scaling

up the design made it evident that assembling modular elements would streamline construction. It also revealed that the installation's self-weight distorted the geometry and necessitated joint reinforcement.

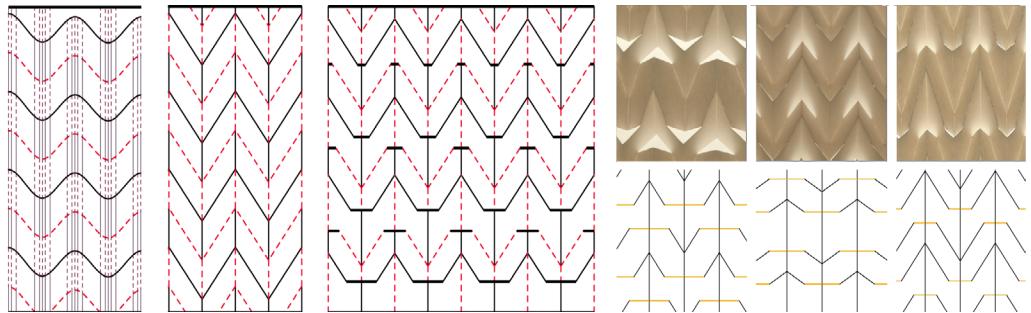
To adapt the paper-folding studies to more practical architectural application, we focused on sun-shading screens. In seeking the elegance and efficiency of origami, we looked at working with a continuous roll of sheet material rather than the more common assemblage of individual responsive folding modules (Ramaswamy, Mingallon and Karatzas 2010).

Linear repetition of motifs in a 2D frieze pattern, that alternate mountain (convex) and valley (concave) folds, can fit orthogonal window geometry. Patterns illustrated have underlying accordion pleats, sine waves, or chevron patterns whose spacing and amplitude and amplitude may be parametrically varied. While parabola-shaped



Figure 2
Compressed Petal (l), Tensioned Petal (c) and Chevron screens (r) present decorative patterns in lieu of the view.

Figure 3
Sine wave and corresponding herringbone Chevron patterns can be clipped to admit light. Proportions of apertures tuned with Grasshopper software to adjust daylight transmission.



folds create compelling visual effects and flex into a conic surface, when combined into wavy sinusoidal curves, they resist folding flat. A sine wave has a corresponding sharp-cornered zigzag that folds flat, and a linear repeat pattern of alternating concave and convex sinusoidal curved folds has a corresponding zigzag herringbone or chevron pattern. Diagonal folds provide canted surfaces to cast shadows and reflect light. In one Petal version, vertically flipping the cut motifs on alternate mountain and valley spines accords the pleat pattern to make the petals move in the same direction so they work together to bounce sunbeams farther. The dimension of the petal was set by maximizing the openings for light while maintaining enough of the accordion pleat surfaces to create a lattice-like frame.

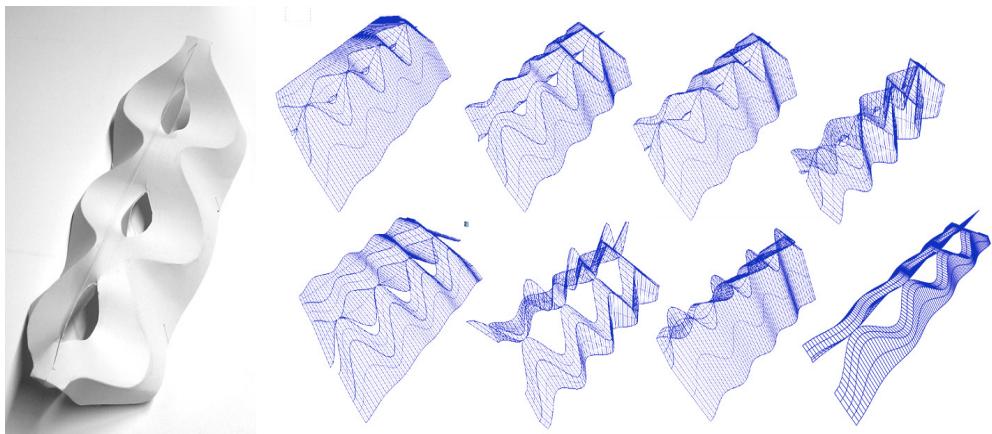
Parametric modeling has been fruitful in the development and refinement of 2D lasercutting

patterns; however 3D folding kinematics have been more challenging to model. Visual inspection of digital models does not reveal when surfaces would need to stretch. More accurate parametric variations were created through the analysis of iterative trials. 3D forms from 2D folding patterns can be digitally simulated by visualizing key points as rotating around hinge axes or point, then finding the intersection of the resulting cylinders or spheres. The complexity of simulating curved folding operations makes the exploration of emergent 3D form through the manipulation of sheet material more direct than digital methods, particularly because folded models often can flip between different stable configurations.

MODELING DAYLIGHTING EFFECTS

To better understand the architectural application of these screens, we built a scale model of an existing

Figure 4
Initial Grasshopper modeling of paper motif (l) did not constrain surfaces from stretching.



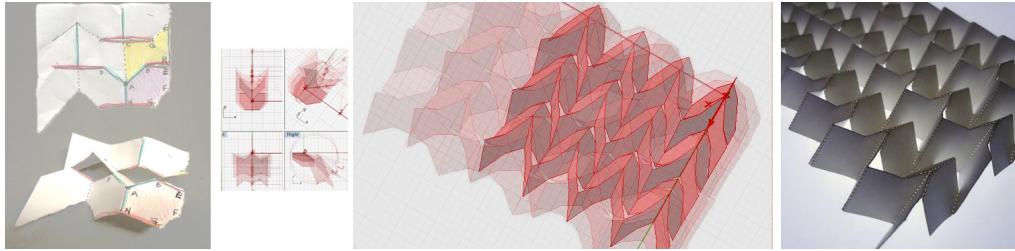


Figure 5
The kinetic simulation for V-weave folding came from studying the cut and folded physical artifact.

classroom with a south-facing window and examined how the screen worked under both sunny and cloudy conditions. To test the differences between the screen when compressed versus when taut, two screens were created using the same geometric cut-outs: Compressed and Tensioned Petals. The screen when Compressed transmits more light, when Tensioned, it blocks more light. Following Köster (2004), a secondary fold in the angled plane gives more light blockage while maintaining more view. We used a heliodon, a calibrated sun-angle table, to understand the screen's ability to shade direct sunlight in three different seasonal lighting conditions - summer solstice, equinox, and winter solstice.

To simulate the diffused light distribution of an overcast day, Additional photos were taken under a mirrored-box artificial sky to simulate the diffused light distribution of an overcast day. Light sensors allowed us to compare daylight factors for the two configurations and

see the light fall-off with the depth of the room.

DAYLIGHTING RESULTS

Images taken at hourly intervals show that both screens successfully shield direct sunlight in summer, reducing heat gain and glare. In the equinox condition, some patterned light enters the front of the room. During the winter, both screens allow sunlight to penetrate deeply into the space.

Under the overcast sky conditions, the screens block more than half the incoming light. In blocking slightly more light, the screen in Tension diffuses it more evenly. While blocking more of the view beyond, the Tensioned screen more effectively reduces glare and creates a more visually pleasing pattern than the compressed screen. Ultimately, the adjustable screen would prove to be most effective in the spring and fall due to the variable sunlight in the season. In the winter the screen is likely to be removed or slid aside in order to maximize seasonally desirable light

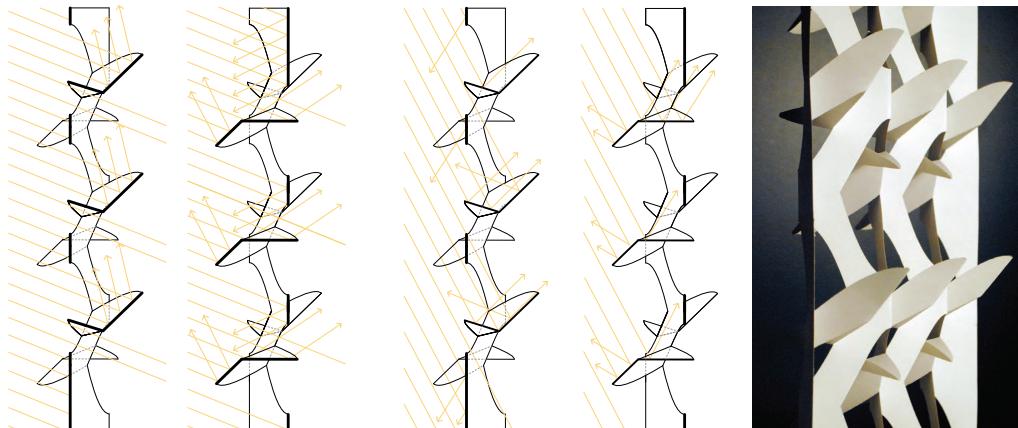
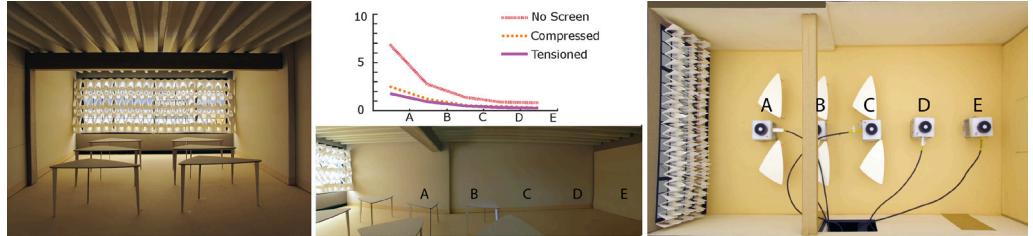


Figure 6
Petal pattern flips petals on alternating convex and concave folds to transmit Winter sunlight (l) and reflect in Summer. (r).

Figure 7
Tensioned Petal screen blocks direct sun in summer (l) and equinox (c), admitting sun during winter (r).



Figure 8
Graph shows similar Daylight Factors for more open Compressed screen (l) and Tensioned screen shown in Figure 4.

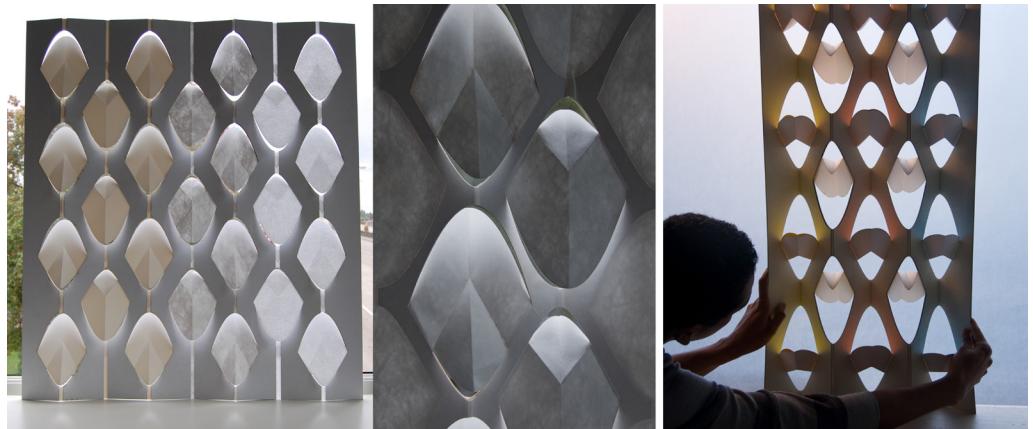


and heat gain. A summary can be seen online [1].

As the testing highlighted the need to bounce sunlight deeper into the space for better daylight distribution, options such as increasing opening dimensions and surface reflectance are being examined. The screen's aperture shape, fold pattern and mounting system could be adjusted for different facade orientations and functional requirements.

MATERIAL AND CONSTRUCTION DEVELOPMENT

Figure 9
Material experiments are needed to take the concept into architectural scale. Layered screen (l) with Yupo polypropylene, Tyvek polyethylene and polyester felt petals on a cardboard screen. Narrower acrylic frame supporting Tyvek petals maximizes translucency (c), bounced color screen.



Digital development of geometry is complemented with hands-on prototyping. Working with physical models foregrounds material characteristics. Constructing the screen prototypes in alternative materials made the divergent performance criteria more evident. In addition to having visual properties of high reflectance and moderate translucence, the screen materials needed to be flexible to fold yet rigid enough to hold shape. In creating screens greater than 1 meter wide, we found no single material could meet all the criteria. The in-

ability of one material to meet visual, structural and requirements led to a search for materials that could be laminated to address the performance criteria. For example, we used 1/8" acrylic sheets to create a rigid frame adhered to a layer of pliable Tyvek petals, pre-tensioned with rubber bands.

Scaling up the prototypes makes component and connection definitions drive the design refinement: the dimensions and flexibility of materials change how connections can be made. At a table-top scale, lasercut or etched perforations can efficiently create self-hinges for folding many materials. We found that plastics such as Yupo polypropylene, and materials with non-directional fibers, such as Tyvek polyethylene and mulberry paper, can sustain partial cuts more successfully than layered paper boards. At a larger scale, shapes need to be adjusted for thicker, stiffer materials. Whether patterns generated with a laser may be scaled up for production through die-cutting, depends on the intricacy of the pattern as well as the material to be cut.

Physical construction reveals how rigid and soft materials could be combined, how fasteners

could work and how components could be assembled. Manipulating hand-held models clarifies the structural loads caused by self-weight and activation. An alternative to optimizing and streamlining a layered assembly could be engineering a custom sheet material with variable stiffness in response to localized requirements.

PROCESS ANALYSIS

The development of the screen designs benefited from the mix of media. Geometric form, interaction and performance can be effectively investigated with computation, while the optical and tectonic possibilities of materials are fruitfully explored in physical constructions. A designer manipulating a material can directly sense how attributes such as reflectance, flexibility and durability will affect a construction and the serendipity of free arrangement can lead to new possibilities. For example, forming the paper around sinusoidal curves, the designer can observe how light and shadow gradients emerge.

For this project, form-finding happened with paper models, then digital drawing and parametric

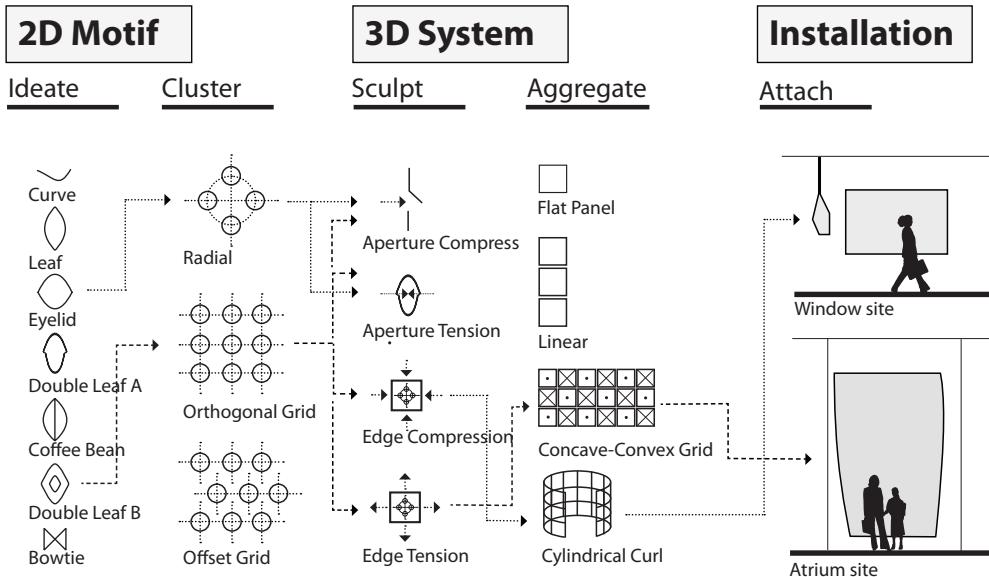


Figure 10
 Process analysis by William Robert Taylor: understanding from each scale informs the next scale of development.

modeling helped generate variations and refinements. A digital model facilitates concurrent digital testing (exporting to analysis software) and physical testing (laser-cutting for use with the heliodon and artificial sky). The screens can be parametrically optimized to better distribute natural light into spaces with specific place-based climatic requirements.

Site-specific problems complemented the broader understanding of an adaptable family of forms from open-ended formal investigation of 2D surface to 3D light modulator. The Shaping Light's Veil installation provided challenges of scale. The classroom window's rectangular shape constrained the screen investigation to linear repeat patterns and diagonal folds. While the two problems generated different design process paths to address unique requirements, in both cases physical mock-ups were crucial to understanding how to direct the digital interpretation.

IMPLICATIONS: NEW FRAMEWORK FOR HYBRID DIGITAL FABRICATION

Hybrid design that constantly crosses between physical and digital requires new support structures, new frameworks. Conventional sketchbooks, workspaces, disciplinary boundaries are ineffectual. If the intention is to generate concepts from material properties, sketching an idea means working out forms and connections both sculpturally and algorithmically. According to architecture Professor Daisy O'lice Williams the new meaning of "sketch" is a conjectural design experiment in any media. The Shaping Light project embraces this, requiring the paper sketchbook to be complemented with a digital scrapbook and physical-analog models.

The digital scrapbook can provide integrated access to photos, videos, parametric families, code chunks, etc. It is usefully organized in a visual filing system that can be accessed online by date or keyword, and is protected with levels of privacy. We throw work in progress onto a remote servers, using file and folder naming conventions that include dates allows tracking of version evolution, putting top images on a photo-sharing website (<http://www.flickr.com/photos/chengo>). Nicknames for design alternatives can ease communication and distinguish-

es branches of a form family. Non-visual information such as Grasshopper code should be annotated both comments and images to clarify the functionality of each section. We have summarized our work onto a Wordpress blog so that it is easily updated, expanded and edited. (<http://aaablogs.uoregon.edu/light>)

Designers need to quickly move between clean horizontal surfaces for paper and dust-intolerant computers, as well as workshops with different types of environmental pollutants (dust, fumes and noise) and machine hazards. The need for a variety of equipped workspaces can instigate interdisciplinary collaboration. At the University of Oregon in Portland, common software classes and machine shop orientation provide both a shared space and a lingua franca of digital fabrication for those in Architecture, Product Design and Digital Art. While end objectives may vary, architects, designers and artists are brought together through a common interest in material manipulation to generate built form. To accommodate new multidisciplinary form of working, space layout and scheduling needs to be planned so that a single day can encompass conceptual discussions, quiet individual research and development, digital and physical hands-on demonstrations and as well as collaborative work sessions.

While defining a specific path through physical prototypes, digital modeling and analytical simulation may sound appealing; our project's less linear development revealed the opportunities of a looser agenda. Developing the Shaping Light work through studies to investigate form, optics, constructability, and installation, revealed these guiding principles:

- * To define and maintain a focus, combine free-exploration of variations with analysis and editing.
- * To keep the investigation fresh, move between different ways of working and different scales, looking for opportunities to re-read the project.
- * To create a robust product, seek site-specific installations that drive performance constraints.

Design requires a balance between free play and discipline, as occasionally a tangent offshoot can seed a new branch of inquiry. Familiarity with a wide range of techniques gives designers the agility to integrate appropriate approaches for each phase of new situations. as each project will require a different set of tools.

Developers can help facilitate the seamless movement through physical-digital translations and interoperability between software programs.

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[1] Rodriguez, Abraham and Nancy Cheng: 2011. Shaping Light video files. <http://www.youtube.com/user/AbrahamNRodriguez>