ABSTRACT

This research investigates the effect of curvature, at a variety of scales, on the acoustic properties of glass. Plate glass, which has predictable and uniform acoustically reflective behavior, can be formed into curved surfaces through a combination of parametrically driven auxetic pattern generation, CNC waterjet cutting, and controlled heat forming. When curved, plate glass becomes “activated,” and complex acoustically diffusive behavior emerges. The parametrically driven auxetic perforation pattern allows the curvature to be altered and controlled across a formed pane of glass, and a correlation is demonstrated between the level of curvature and the extent of acoustically diffusive behavior. Beyond individual panels, curved panes can be aggregated to extend acoustic influence to the entire interior room condition, and the pace at which acoustic energy is distributed can be controlled. In this work the parameters surrounding the controlled slumping of glass are described, and room-sized formal and acoustic effects are studied using wave-based acoustic simulation techniques. This paper discusses the early stages of work in progress.
INTRODUCTION
Glass and Acoustics
Building interiors are predominately flat and orthogonal. By default, these attributes preserve sonic content in the form of sustained reverberation and repetitive sound propagation paths. Such spaces can be acoustically harsh and poor for concentration and communication. Manipulation of sonic character via surface shaping offers the potential for interior acoustic performance that balances comfort and function. Glass offers unique attributes of crisp visual transparency, durability, strength, and formal malleability at a wide range of scales (Neugebauer 2014). Glass can modulate acoustic qualities through its geometric configurations and finishing. This research seeks to explore the variability offered by glass through the development of individually customized curved panels and their aggregation into intimate spaces that key into a distinct aural experience. Utilizing perforation and curvature to “activate” glass by changing its form opens it up to such performance.

Previous Research
Activating curvature builds upon these key attributes of glass, as well as upon previous research that covers manipulation of both the geometric and optical effects of the material (McGee, Newell, and Willette 2012). Driven by the inherent benefits of double curvature to the strength of thin materials, this research focused on the potentials of shaping glass into complex geometries through contemporary digital fabrication techniques. Utilizing a custom-built reconfigurable pin-mold embedded into a kiln, the equipment and software developed for Glass Cast (Figure 2, top) ties very specifically to particular material attributes, providing the potential for continuous variability in geometric output while reducing the waste associated with dedicated molds. The research that followed, in Specimen (Figure 2, bottom), relates specifically to the immaterial attributes of the material system, most notably the light effects seen in reflection across the developed curvatures.

Simultaneously, research has progressed on the relationship between enclosure and acoustic behavior. The underlying theory recognizes the continuum that connects acoustically reflective (low surface area), diffusive (moderate surface area), and absorptive (high surface area) applications and forms (Belanger 2016). The common notion of “acoustic material” is a misnomer since the formal configuration of material primarily determines its acoustic properties. Glass, for example, can be acoustically reflective (planar), acoustically diffusive (curved in two dimensions) or acoustically absorptive (small-diameter fibers in a batt configuration). Plate glass and fiberglass are common in contemporary architecture, with their acoustically reflective and absorptive properties readily utilized. The curvature scales that fall between these two, however, have scarcely been explored in architecture. This works seeks to help fill the gap and complete the continuum for the performance of glass.

Building off of these previous studies in glass and acoustics, this research explores the geometric manipulation of the material and immaterial properties of glass at a variety of scales, working in the continuum between acoustic reflection and diffusion.

Notes on Acoustic Parameters
Traditionally, acoustic behavior in rooms is assessed with parameters such as reverberation time, which is the time required for sound in a space to decay by 60 decibels. These parameters have been motivated by and correlated with perception, and generally with room function. For spaces where speech is important, for example, a low reverberation time of less than 1 second is considered...
desirable. For unamplified music, longer reverberation times of 1.8 seconds or more are often suitable. Reverberation time can be predicted by calculation or simulation using the shape of the space and the acoustically absorptive properties of its materials. For the work described in this paper, however, we have pursued a more spatial perspective of sound; one that is more interested in the dispersive properties of surfaces than in statistical parameters such as reverberation time.

METHODS

Kiln
In order to study a range of possibilities in slumping glass to inform the concepts described above, a custom pin-mold kiln and related kiln furniture was designed (Figures 4 and 5). The working area of the kiln is limited to a rectangular volume 4’ deep x 3’ wide x 2’ high. Kiln furniture, such as frames or drop rings, is made to create fixed edges to hold the perimeter of the glass. These elements allow the glass to slump freely without the obstruction or requirements of rigid molding across the entire pane of glass.

The kiln utilizes a standard ramp-soak proportional-integral-derivative controller to provide precise control over the forming cycle. The temperature settings for the glass are established by testing standard glass-forming temperature cycles as they relate to specific glass-melting points and thicknesses (Spectrum Glass 2005) and the observed performance of the kiln. For the tests associated with this paper, 4 mm privacy glass was used, with temperatures reaching a maximum of 1170°F.

The perimeter of the panes of glass, and how it relates to the final form, has proved to be critical in the development of curvature and larger, aggregated, overall forms. To better understand the internal curvatures produced by various forming temperature cycles, a fixed frame was used. The glass begins as a flat sheet and curves in two dimensions as it forms under its own weight. By holding the frame size constant and increasing the soak time (the duration of time the glass is left at its slumping temperature), a set of controlled slumps was made. These elements are then laser scanned for comparison to slump simulations, insertion into acoustic simulations, and development of a workflow for registering, simulating, and documenting all tests moving forward (Figure 6).

The controlled slumps provide a base set of geometries that correlate slump curvature and depth to the kiln-forming cycle on a single pane of glass. These panels provide a base of comparison for results that are created by further modifying the glass pane prior to slump, in this case through the CNC waterjet cutting of slits or perforations to the surface.

Since the slumping process stretches the pane, with the most apparent movements happening in the z-direction due to gravity, cuts in the surface open and induce material stretch during the kiln cycles, altering the local geometric curvature across the panel. The location, length, and density of the cuts affects the depth of the slump as well as localized details in the form of smaller curvatures, openings, and flared edges. While these results are less predictable, they indicate that variations in cut patterns produce changes in the overall curvature of the pane. This
led to a series of tests in various patterns (Figure 7). The
initial patterns focused primarily on the direction of the
slits as they related to one another. For example, lines were
tested in parallel, v-cut, and arrayed conditions.

**Acoustics Form Considerations**
Most non-flat surfaces—with the exception of large-radius
concave surfaces—diffuse sound to some degree. Even
small-radius concave surfaces diffuse sound because
reflected energy passes through a region of high density
and is dispersed beyond that. This points to infinite design
possibilities for intentionally diffusive surfaces, especially
if surface shape can be correlated with the severity and
character of diffusive behavior. The relationship between
the geometry, scale, and wavelength of diffused sound is not
precisely understood, but generally dimensions of at least ¼
of the largest wavelength (lowest frequency) to be diffused
are effective. The size of the kiln used in these studies
allows for curvatures and depths that correlate well to the
audible wavelengths of the human voice (of which about 4’
can be considered a reasonable maximum). Additionally, the
aggregation of individual panels into larger systems lends
an opportunity for more aggressive diffusive systems.

**Acoustics Simulations**
Acoustic simulations were conducted using a wave-based
finite-difference time domain (FDTD) computational method,
specifically a 2D compact explicit standard leapfrog
scheme (Kowalczyk 2008). Simulations were conducted
using the following procedure:

1. Specify panel geometry in CAD environment by drawing
directly, simulating the geometry, or importing a laser
scan of the physical panel.
2. Choose a 2D section of the panel for study. If a room or
any other aggregate system is being studied, assemble it
into a 2D representation.
3. Use a custom-made parametric script (Grasshopper),
discretizing the curves into points at a specified resolu
tion and exporting them as coordinates into a text file.
4. Import the coordinates into a custom MATLAB script,
where they are “snapped” to a suitable grid and
resolution.
5. Seed and advance the simulation to calculate the energy
of the sound field at every point for each timestep. An
image file is also created for each timestep, which can
be studied individually or assembled into animations.

Unlike more common geometrical acoustical simulations,
FDTD calculates the wave behavior of sound, which includes
phenomena such as diffraction and interference. The
simulations are limited to 2D, the boundaries are treated as
perfectly reflecting, and the absorption of air is not taken
into account. These limitations are justified because they
keep computational time reasonable and they underesti-
mate the performance of glass (e.g., real glass would do
better than in the simulation because a small amount of
additional energy would be removed at each reflection).

**Auxetic Patterns**
Of the numerous perforation patterns studied, auxetic
patterns provided the most potential for controlling the
Example of curvatures induced by slumping auxetic patterns.

curvature (Konakovic et al. 2016). During the forming process, the pattern unwinds or twists and simple line slits become larger openings. Where auxetic patterns are located, material moves more freely in the z-direction than in regions without the pattern, as the glass stretches under its own weight. The ease of movement ends abruptly at the pattern’s boundaries and inflection points are introduced that give rise to more complicated double curvatures. This produces interesting geometric variations and possibilities, including anticlastic (saddle) surfaces, allowing varied and smaller curvatures within the same fixed frame (Figure 9).

To explore this further, a set of auxetic pattern conditions was developed to create more complex curvatures. The focus of these studies centered on edge conditions, starts and stops in the pattern, variable densities, and variable slit lengths.

Each test has been laser scanned for formal study and for the development of more rigorous slumping simulation models. This method of pre-slits into the glass combines curvatures and perforations in an interrelated surface condition. In doing so, we believe that we can control final form using auxetic patterns.

RESULTS

The acoustic simulations were conducted by taking a section through various slumped panels, and applying these sections to the perimeter of a rectangular space to create a “treated” 2D space. Different degrees of slumping were explored from zero (flat rectangular space) to heavily slumped.

The results show that the more heavily slumped the glass, the more quickly sound energy is mixed in the space. The definition of a precise “mixing time” is somewhat arbitrary and debated in architectural acoustics, but in this context it can be defined as the amount of time it takes for sound energy to become evenly distributed in a space (Belanger 2012). Regardless of the exact definition, the trend of faster mixing with increased surface curvature (more aggressive slumping) is clear.

In the context of computational design, parameters that govern the severity and form of slumped glass are controlled, and the slumping that results is correlated to acoustic behavior. In other words, the parameters of slumping provide a direct path to the determination of an acoustic goal, in this case the time it takes to mix sound energy in a space.

CONCLUSIONS

The careful articulation of form and its intentional entanglement with aural performance provides the ability to transform environments through the use of glass. New formal manipulations and production processes will be launched to target desired results, with each new module and enclosure providing the opportunity for acoustic analysis, each pointing to a potential glazing application.

The next steps will compare slump simulations to laser-scanned forms, move acoustic simulations and physical tests up in scale, include robotically positioned physical acoustic measurements to correlate with simulations, and develop a design feedback between analyzed curvature and slumping behavior. The fixed perimeter of our slumping frames will take on new, non-planar geometries as a means to induce other types of curvature.

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REFERENCES


**IMAGE CREDITS**

All drawings and images by the authors.

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10 Acoustic simulation stills of 2D rooms of equal area, using identical source of sound, each taken at the same time in the evolution of the sound field. From left to right: planar glass, lightly slumped glass, and heavily slumped glass. Note that with increased total surface area, there is a quicker mixing of energy from left to right.