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Light Forms: Modular Variation, Pattern, Structure

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Abstract

Light Forms is a compressive glass block system aimed at creating site-specific architectural structures that investigates three-dimensional forms studied for light transmission and structural performance. Building on the success of previous cast glass architectural blocks, *Light Forms* expands this work by adhering two components to create a single glass modular unit that offers the following unique opportunities. First, through the process of industrial press forming, mass production on the industrial scale is possible. Secondly, hollow voids created in the pressing process offer unique opportunities for prismatic effects, and controlling light transmission and privacy, in addition to creating an encapsulated air pocket while still maintaining thick walls. Next, the necessary adhesive joint to adhere the two halves together becomes an opportunity for deploying color shifts through dyed adhesive joints and considerations for reuse through reconfiguration and feasible furnace recycling. Lastly, the overall form of each modular unit is a decahedron designed in a manner that through the change of orientation tessellates into various patterns. Utilizing offset stacking, the patterns can also introduce angles and curvatures across an architectural wall while taking advantage of the compressive strength of glass. *Light Forms* investigates the correlation of geometry and structure as it also relates to optical performance and design opportunities.

Keywords

structural glass blocks, variable tessellation, interchangeable internal volumes, industrial press glass processes, optical opportunities

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1. Introduction: Glass Blocks

In the realm of building materials, glass integrates the rare combination of compressive strength and light transmission, while also being an inert material. This makes a primarily glass material system well suited for structural and optical performance.

The *Light Forms* design (Figure 1) builds off the previous research undertaken toward solid glass modular units and current industry standards. The standard glass block design, widely produced by Pittsburgh Corning since the 1930's (Fagan 2015) utilises glass press casting technology to mass produce glass building units. Recent precedents, such as the 2007 Atocha Memorial in Madrid by FAM architects with structural engineering completed by Schlaich, Bergemann und Parnter, demonstrated how curvilinear edges on the glass block can introduce variation to the building's geometry using only one block (Göppert & Paech, 2006; Paech & Göppert, 2008). The 2016 Crystal Houses (MVRDV design with TU Delft technical research) and the 2021 Qaamaat Pavilion (Konstantin Arkitekter design with TU Delft technical research) offered deep investigations toward approaches in construction and adhesive strategies (Oikonomopoulou & Bristogianni, 2022; Hayez et al., 2021). The *Light Forms* design propels that work in the following ways:

1. Integrates a design that can tessellate in varying orientations and patterns.
2. Explores the opportunities associated with press casting glass to achieve a hollow interior, dimensional consistency, and repeatability, toward a structural glass block building system that can be scalable with industry production and maintain a wall thickness that contributes to structural performance.
3. Investigates transparent adhesive choices that offer structural construction using press glass units with as-cast surfaces that in construction are not necessarily parallel to the ground and creates the potential for reuse through reconfiguration.
4. Strategically deploys solid and voided forms for optical, structural, and assembly details.

This drives architectural designs where glass is used as the main material for spatial, structural, and light transmission of the space, encouraging an ethos of passive lighting and connection with the surrounding environment. The design of *Light Forms* focuses on external self-carrying walls, initially undertaken in single story scenarios. With these capacities achieved, the system can also be used for external non-load bearing walls, and interior walls. The thickness of the glass and relevant stacking patterns provides more structural integrity than what can be achieved with the non-load bearing, stacked pattern of conventional hollow glass blocks (International Building Code, Section 2110).

Extending beyond construction opportunities and constraints, the *Light Form*s project is also deeply rooted in an approach to architecture that places the transmission of natural light and darkness through complex optical distortion. Anchored in the optical and geometrical research of novel glass modular units, the key to *Light Form*s is to transmit and translate the surrounding light and colors while also working structurally. In this manner, the light qualities of both day and night are fundamental to the experience and operation of a space impacting the circadian rhythms and cognitive rest of the inhabitants.

Fig. 1: Light Forms, asymmetrical void prototype aggregation.

Fig. 2: Fluorite, quartz. Carles Millan gallery, Creative Commons, https://carlesmillan.cat/gallery/

2. Geometrical Pursuits: multiple orientations and patterns

2.1. Crystalline Structure

The base geometries for the *Light Forms* design were initially inspired by crystalline structures. As demonstrated in nature, the polyhedral forms of crystalline structures can tessellate in various patterns and possess complex relationships to light in terms of reflection and transmission across the numerous facets. (Figure 2). These qualities demonstrate the potential for spatial and complex glass geometries within architectural structures that can contribute in novel ways to both structural and optical logics as transparent buildings. Light signatures can be augmented within an architectural space through building with different tessellations of the same glass unit (Figure 3).

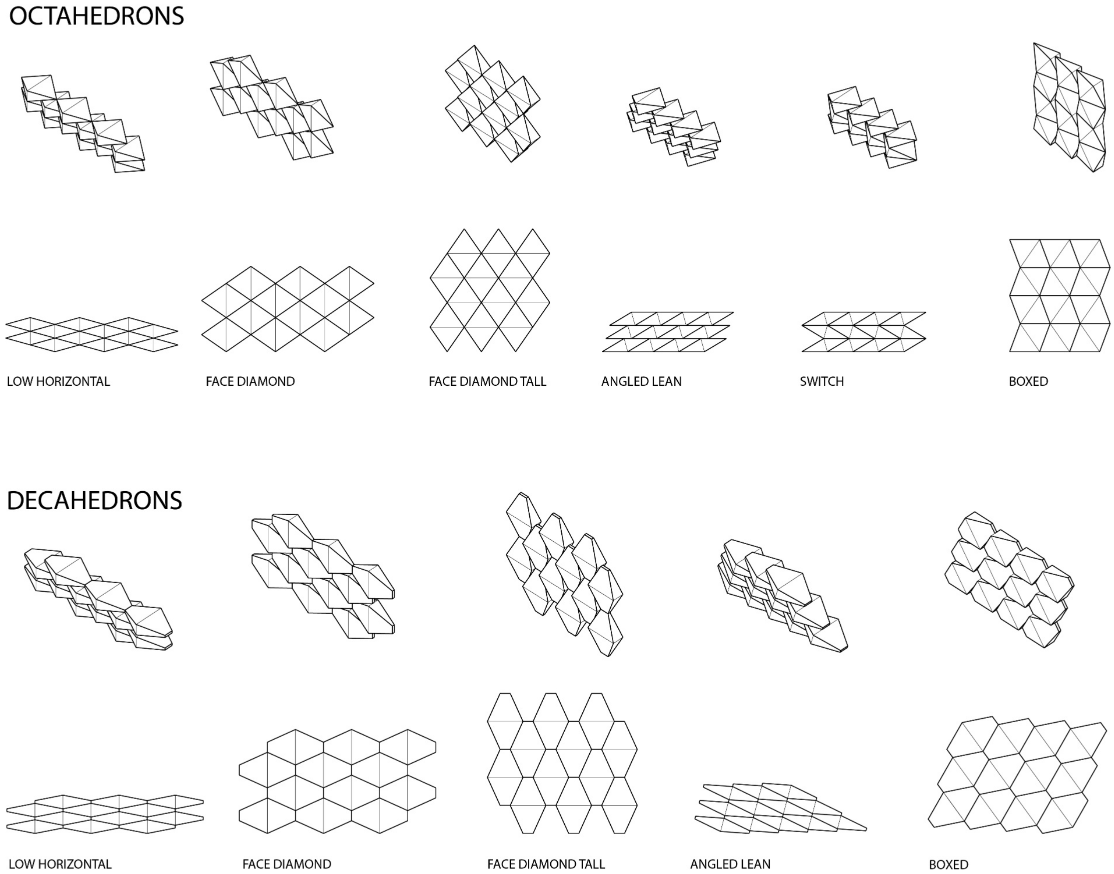


Fig. 3: Light Forms, tessellation patterns for octahedral and decahedral module forms.

2.2. Octahedral Design

Initial designs fully embraced sharp crystalline facets with pointed tips, and an octahedral form tetragonally distorted (Figure 4). This design exhibited many advantages in terms of tessellation variation due to the form exhibiting two different axes of bilateral symmetry. The associated angles and proportions allow for several patterns that through perfect alignment create fully sealed enclosures from one side to next.

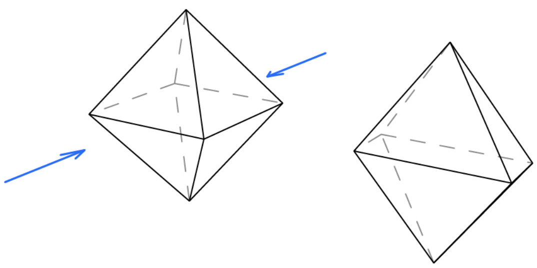


Fig. 4: Light Forms, an octahedral form that is distorted twice with tetragonal distortion.

Fig. 5: Octahedron and decahedron forms with voided interiors.

2.3. Decahedral Design

Due to capillary action of the glass and cooling at the extremities of the mold, the tip of the form would not easily fill and round over, causing a small gap between units that would have to be filled with extra adhesive (Figure 5). Where the original octahedral design exhibited satisfying aesthetic and optical qualities, to ensure a fully sealed building envelope, the design evolved to a decahedron form with a truncated tip (Figure 6, 7).

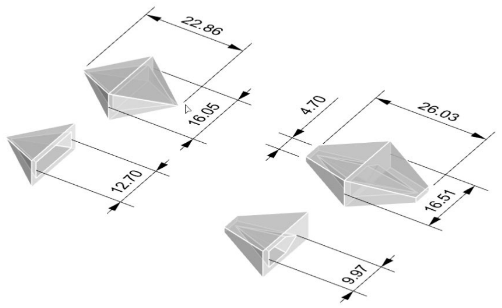


Fig. 6: Design evolution from octahedral to decahedral form

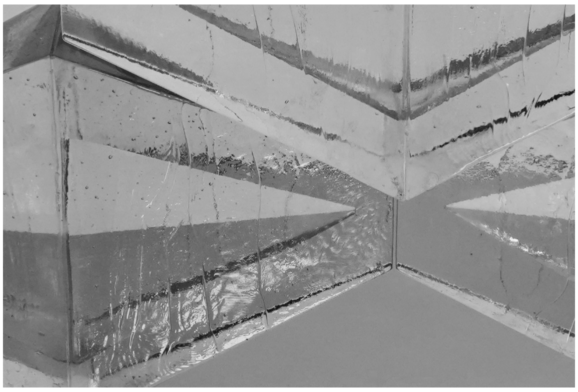


Fig. 7: Detailed images of the decahedron face alignment

2.4. Variations with Self-similar Forms

The crystalline form lends the module to distinct variations in tessellation. Some of the tessellation patterns relate closely to one another, where the major variation is dependent on which face the form leans on, for example the "Angled Lean" variations relative to the "Low Horizontal" tessellation (Figure 3).

While the introduction of the truncated tip that moved the octahedron base to a decahedron form eliminated some of the fully sealed patterned options (i.e., the octahedral "Switch" variation), it also permitted the introduction of curvature within a sealed course. Neighbouring forms can be incrementally shifted in alignment in one direction, generating curves. Using a custom Python plugin within Rhinoceros software, incremental movements of each individual glass unit are calculated to create an overall wall assembly possessing sweeping curves (Figure 8).

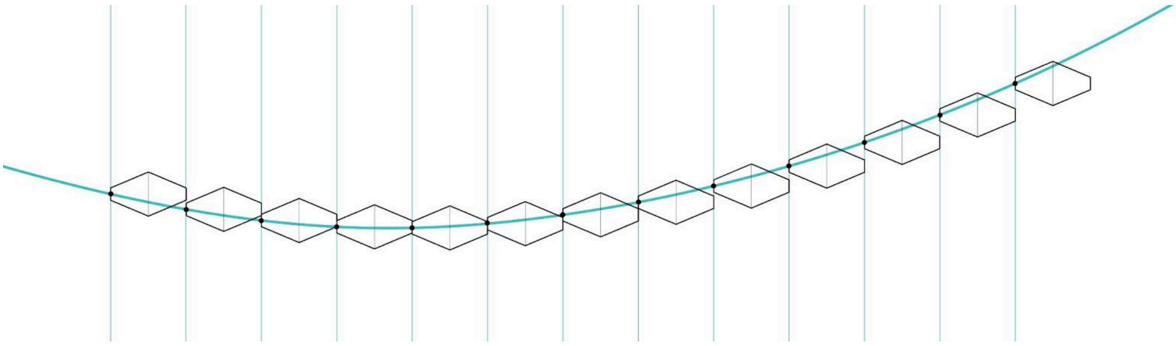


Fig. 8: Decahedron Light Forms modules allow for incremental shifting in one direction, inducing curvature along a course.

If a structure does not need to be fully sealed across an entire wall, then patterns can vary further. For example, exaggerated curvatures can be created within a course if modules can shift in a manner that allows for openings between units. Within the construction of a larger pattern, shifting courses relative to the course below allows for the introduction of angles within the wall. These formal variations can be used together to create complex and varying surfaces in a self-supporting structures (Figure 9).

Still further, multiple tessellation patterns can be used within the same spatial design for optical, structural, or aesthetic variations.

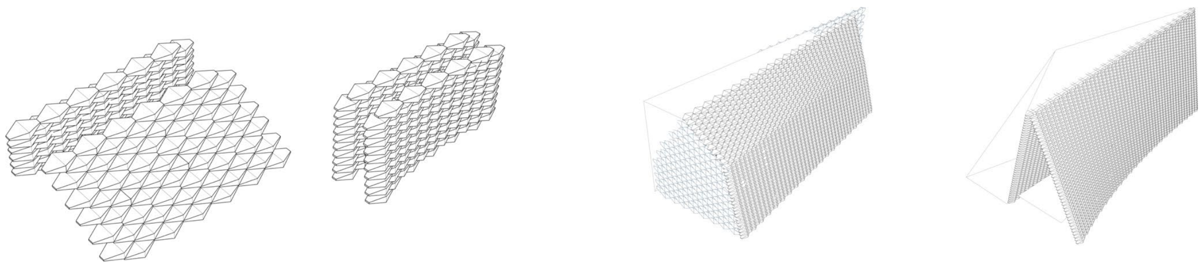


Fig 9. Stacking variations of angles and curvatures, and larger spatial examples achieved by incremental shifts between blocks and courses.

3. Prototyping and Fabrication

3.1. Press Casting Process

The Light Forms design uses press casting, a common glass manufacturing technique for creating complex solid shapes. In this process, a specific amount of molten glass is poured into a mold. A plunger then presses into the mold, creating a void in the glass shape, as illustrated in Figure 10. This method ensures detailed sharpness without rounding off, except for extremely sharp points like the tip of the octahedral shape which exceeds this capability. Once slightly cooled, the glass solidifies, allowing the plunger and mold to be removed with minimal shrinkage if the design has relatively uniform thickness. This technique also reduces the need for coldworking, and possibly eliminates it altogether based on design, adhesive choice, and glass quantities. Additionally, it supports using different plungers with the same mold base, offering versatility.

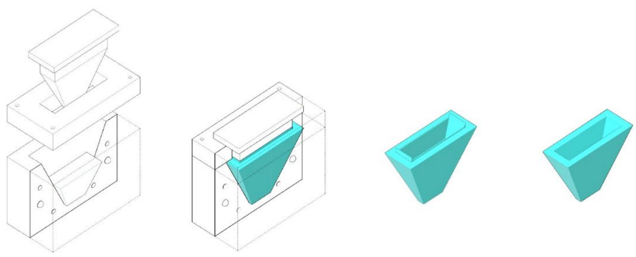


Fig. 10: Form created through a press casting process.

3.2. Two Halves

Easy and efficient mass production is a core objective of the *Light Forms* design. The project strategy uses two halves to construct each module. This method allows for the creation of larger units that were otherwise inefficient to produce due to either the weight or the time it would take for a single cast to cool.

An added benefit to this design approach was the ability to create enclosed voids or empty spaces within the forms. This was achieved by encapsulating impressions made with plungers in the glass through the face-to-face assembly of two halves. Solid halves also remain a key variation for the forms in terms of both optical and structural performance.

The inclusion of these voids significantly influenced the design and performance of the modules. Interior voids add a prismatic negative space and additionally reduce the overall weight of each module. The shape of the void does not have to be a consistent offset to the outer geometry. Variations between the inner and outer geometries allow for the investigation of symmetrical and asymmetrical relationships. Internal voids can range in their geometric qualities such as number of facets, the use of curves, or depth of press. The void multiplies the presence of surfaces and facets that contribute to the reflection and refraction of light, resulting in passive lighting within a space while also offering a sense of privacy.

The design evolution of the project carefully balances alterations to outer geometrical relationships, internal offsets, as well as weight and production constraints (Figure 11).

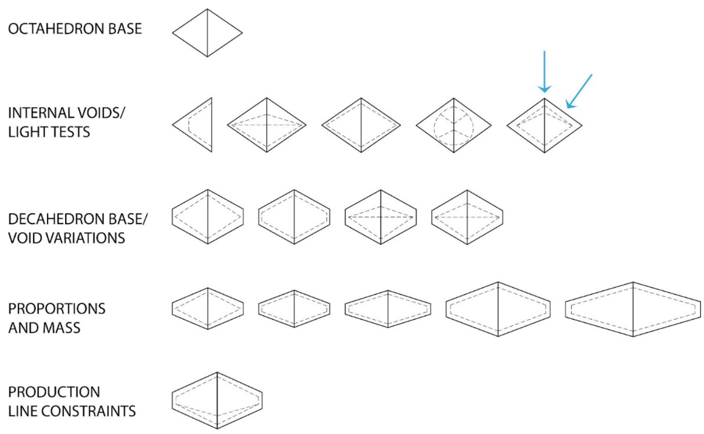


Fig. 11: Design evolution diagram.

3.3. Constraints within the Press Casting Process

The shaping and configuration of the base molds and internal void plungers further affects light passage. At different stages in design development, the sharpness of a corner within the base mold and internal plunger has gone from crisp to radiused in consideration of machining capabilities, heat transfers during production, and mold release. During prototyping, initial lost wax cast testing permitted the sharpest corners, as they were molded from PETG cut and folded shapes. CNC-milled graphite molds introduced a 0.79mm radius to the corner, based on finishing router bit size. Steel mold production on a hand line with an industry partner has moved the internal plunger radius to 3.18mm on edges, and 6.35mm for the tip of the plunger. While the base mold exterior edges were radiused to 1.52mm. All of these design alterations are based on heat transfer concerns and to alleviate glass sticking in the mold. When using a steel or iron mold, if an edge of the plunger is too thin, it can heat up beyond 537°C and temporarily stick to the glass. These slight design changes to support production feasibility do alter the light effects in terms of how the light interacts with a crisp or rounded corner, as well as the difference in appearance of reflected light compared across adjacent faces.

3.4. Adhesive Choices

Adhesive explorations have been extensive, and were evaluated in terms of structural performance, ease of construction, creep resistance, working temperature range, aesthetic qualities, curing time, and capacity to fill minor gaps. Disassembly is also a critical factor in the design. Mortars common to hollow glass block construction and other assemblies limit deconstruction for reassembly, and recycling glass blocks with mortar residue would contribute to significant furnace inner refractory lining deterioration.

Precedent research conducted by TU Delft researchers Oikonomopoulou and Bristogianni was referenced (Oikonomopoulou & Bristogianni, 2022) when developing possible adhesive systems for the *Light Forms* design, specifically on their research connected to the Crystal Houses project and the Qaamaat Pavilion. New (3M DP100- plus clear, PVB, and Dowsil 2400) and previously tested (Delo 4468, 3M Very High Bond Tape 4910) adhesives were studied due to the variable angles of application necessary within the *Light Forms* adhesion areas between modules and opportunities to consider different approaches to adhesion between halves versus the adhesion between units. Each adhesive explored exhibits its own strengths and limitations. The adhesives investigated thus far are the DELO Photobond 4468 adhesive, 3M DP-100 plus clear with Amnio Saline Pretreatment, 3M Very High Bond Tape 4910 (1mm), PVB/Sentryglass, and Dowsil 2400 hot melt silicone.

There were two zones of consideration when approaching choosing a proper adhesive: lamination between the halves to create one complete *Light Forms* unit, and to adjoin the *Light Forms* together in courses to create wall systems.

Adhesive qualities ideal for lamination between the halves:

- Water seal
- Fill approximately 1mm of gaps in areas
- Optical clarity
- Viscosity that does not flow into interior voids
- Rigid bond, with some flexibility

Adhesive qualities ideal for lamination between units to fabricate wall systems:

- Water seal
- Optical clarity
- Flexible bond that offers cushion
- Variable gap filling between courses between 1-3mm
- Viscosity that resists flow due to the angled topography of each course during construction
- Overflow easily removed

The following chart describes the unique potential and deficits of each adhesive within each of these two zones.

Specimen	Adhesive	Description	Benefits	Drawbacks	Further Testing Required	Potential/Notes
1	DELO Photobond 4468	UV and light curing acrylate adhesive, medium viscosity	-UV curing almost instant -Optical Clarity - Very strong bond -Rigid bond good for half to half adhesion	-Glue joint needs to be as minimal as possible or the shrinkage rate of the adhesive causes cracking at thin walls, requiring an additional step of coldworking exterior of glass units to minimal tolerances. -Rigid bond would not provide cushion or flexibility to distribute load across wall assembly.	Eliminated	-Would not work for attaching wall assembly as the gaps caused by surface variation is too great - Shrink rate introduces problems with thinner walls of voided modules.
2	3M DP-100 plus clear with Amnio Saline Pretreatment	Two-part self-levelling, low-viscosity structural epoxy	-Easy to dispense -Optical clarity -High shear and peel strength. - Fast setting -Strong yet slightly flexible bond good for cushion and vibration -Fills minimal gaps	-Lower viscosity, more difficult to apply cleanly. -Rated for outdoor applications, but not tested for hydration creep in seams over time.	-Perform weathering test for hydration creep between halves -Wait a certain amount of time before joining halves can be tested so epoxy sets up and does not run down the interior void.	-Most useful between halves, as it offers a more rigid, aggressive bond than silicone.
3	3M Very High Bond Tape 4910 (1mm)	A clear, 1.0 mm, general purpose acrylic adhesive on both sides of a firm, foam core.	-Easiest application -No special equipment - Optical clarity -Instant green strength -Flexible bond good for cushion and vibration	-Adhesion is not strong enough and too flexible for structural applications that must take on a sizable load.	-Perform weathering test for hydration creep between glue joints.	-Could be a useful material during construction for tacking units in place as courses are laid, and while other adhesives are setting.
4	Sentryglass	Ionoplast laminating interlayer	-Has excellent clarity, adhesion, and safety rating - Performs very well with lamination edge exposure applications	-Specialised processing in autoclave or kiln under vacuum. - Consistently had creep within inner void variations. -Only potential use as adhesive between two halves.	-Testing colour variation at glue joints with solid design variations	-Could be useful for applications with coloured glue joints for solid design variations.
5	Dowsil 2400	Neutral-cure hot-melt silicone	-Good clarity for silicone -Instant green strength -High viscosity/low sag	-Specialised dispenser needed that is expensive and cumbersome for some on site building. -No longer producing smaller tubes of product	-Weather and humidity testing with a humidity sensor inside of the unit. -Compression testing	-This is the strongest candidate for wall construction applications, and potential candidate for half-to-half assembly.

Table 1: Adhesive assembly study.

The hot melt silicone adhesive Dowsil 2400 offers the best qualities for our construction needs thus far: high peel strength, neutral cure, flexibility, instant green strength, and cushioning under compression to distribute loads across the aggregation. Where two-part catalysing silicones have similar qualities, such as the one used in the Qaamaat Pavilion (Hayez et al., 2021), this heat set silicone is formulated in clear (catalyzing silicones are only offered in white or grey) and offers a significant aesthetic advantage for the Light Forms polyhedral design that shows adhesive coloring between aggregation units, especially in offset aggregations for angles and curvature.

4. Structural Testing

To design and scale these systems for large scale construction, it is necessary to study the structural behavior of the system and its potential failure mechanisms. Achieving this involves two primary steps: 1. conducting destructive structural tests on the modular system to study its behavior, composite glass adhesive action, and failure mechanisms and 2. developing a methodology for structural design of self-standing wall systems under self-weight and environmental loads.

ASTM E1300 (2023) standard offers design charts and processes for determination of the minimum lite thickness for a desired load resistance of annealed glass, based on the Glass Failure Prediction Model (GFPM). By applying modification factors to the annealed selection, design thicknesses for other glass types (heat strengthened, fully tempered, laminated glass) can be obtained as well. It is important to understand that the design charts and the process in ASTM E1300 are limited to the determination of the minimum thickness of glass that is simply supported along at least one edge and are limited to rectangular geometries under a uniform load condition. This process is a practical approach for design and engineering of sheet type glass elements, however, due to its fundamental assumptions and limitations it is not applicable for design and engineering of glass masonry type structures, such as the ones in this study.

On the other hand, due to the complexities of the assemblies, including, modular nature, complex geometry of the modules, glass-adhesive composite behaviour, unknown surface defect distribution, and system boundary conditions, implementing a reliable numerical structural analysis of these systems is found to be challenging as well. Moreover, there is not an existing reliable method to identify surface flaw characterization and residual surface stress distribution to apply a statistical analytical design method based on the GFPM.

All these challenges highlight the importance of physical prototyping and destructive structural tests. Towards this goal a series of destructive structural tests were carried out on modular specimens composed of assemblies using different adhesives. The choice of adhesives is a critical subject as it significantly impacts the structural performance and the failure mechanism of the system.

4.1. Compressive Test:

A compressive test was carried out on a specimen to study the structural behavior of the assembly under compressive force. The specimen was composed of 4 modules and 8 halves adhered with a fully cured DELO Photobond 4468. The geometry and dimensions of the specimen is shown in Figure. 12, and the properties of the adhesive are described in Table 1.

The test is conducted with displacement control using a Universal Testing Machine as shown in Figure 13. Due to the asymmetry of the specimen assembly, a non-uniform distribution of stresses occurs in the specimen with maximum stresses occurring in the lower right corner as highlighted in Figure 12.

Additionally, due to the inclined bonding surfaces of the modules, the adhesive joints experience shear stresses under the applied compressive force, which can cause delamination and failure of the adhesive joints.

The results of the test corresponded with simplified simulations and failure predictions. The specimen failed when reaching approximately 27 kN (equal to 1450 kN/m2 uniform stress on the loading surface) and a displacement of approximately 25 mm. At that point, one of the modules cracked in the high-stress region, causing a drop in the load and redistribution of the stresses in that region. Subsequently, the load started to increase again, reaching 30 kN at 33 mm of displacement. The adhesive started to fail in shear, and more modules started to crack, leading to the failure of the specimen.

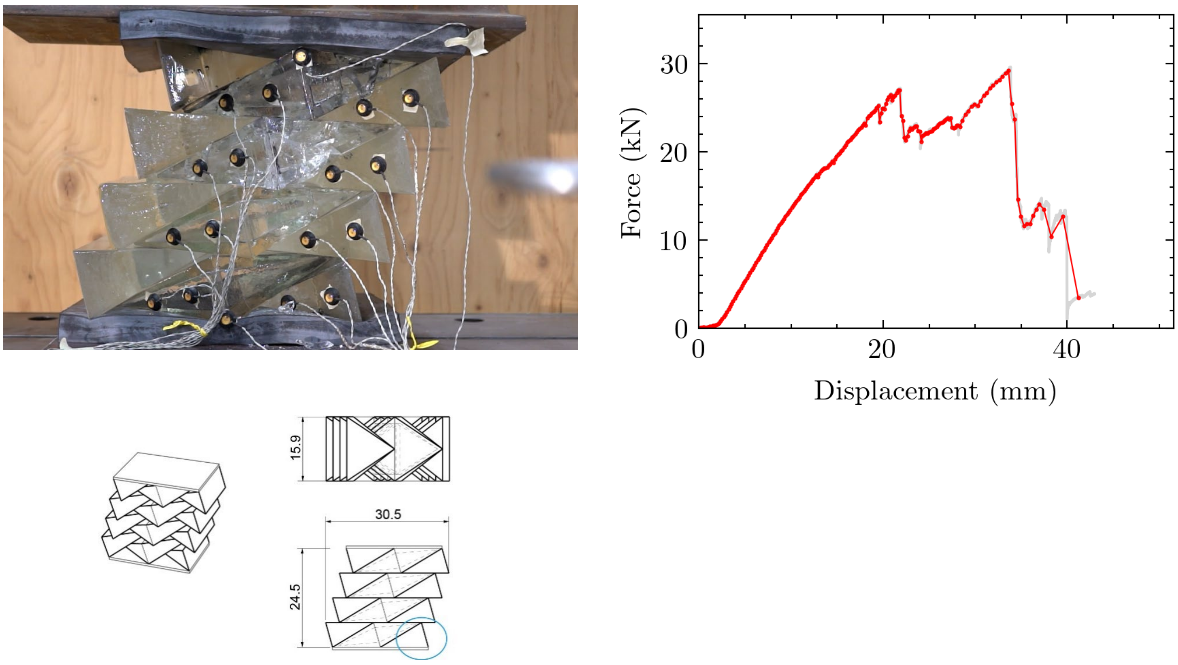


Fig 12: Compression Test Force-Displacement diagram indicates a resettling.

4.2. 4-pt Bending Tests:

Series of 4-point bending tests were conducted on specimens assembled using different adhesive types to study out-of-plane bending of the wall assemblies and the performance of the adhesive joints in shear. The specimens consisted of seven modules forming glass beams shown in Figure 13.

Details about each specimen and the adhesive type are presented in Table 1. The load-displacement graph and test results are illustrated in Table 2 for the five specimens.

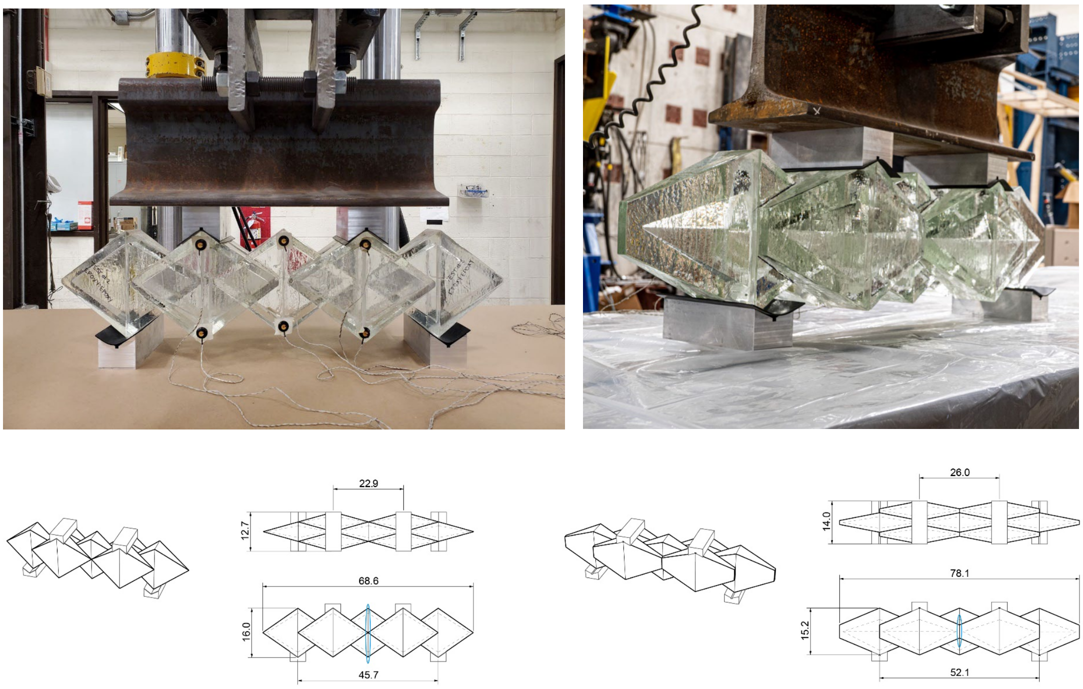
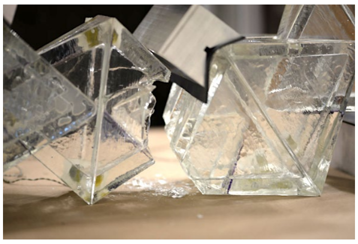
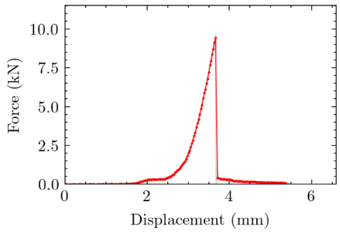


Fig. 13: 4pt Bending Test set-up with displacement sensors.

Specimen 1: DELO Photobond

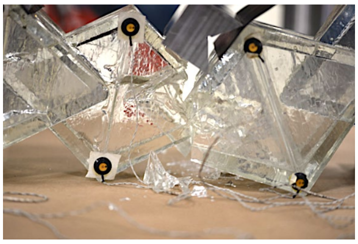
Failure Mode:
- High composite action
- Sudden failure
- Low capacity for redistribution of stresses

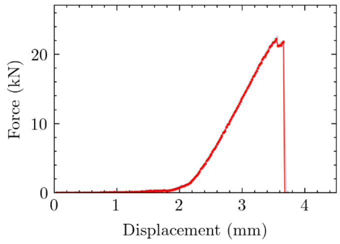




Specimen 2: 3M DP-100 plus clear with Amnio Saline Pretreatment

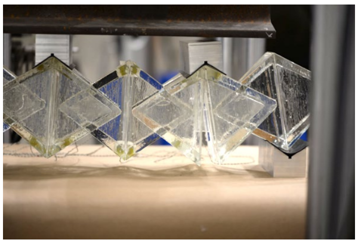
Failure Mode:
- High composite action
- Sudden failure
- Low redistribution of stresses
- 30% lower capacity compared to Specimen 1

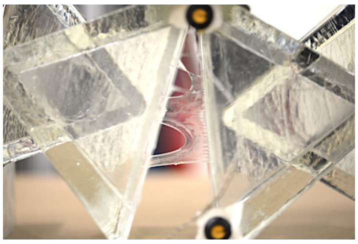


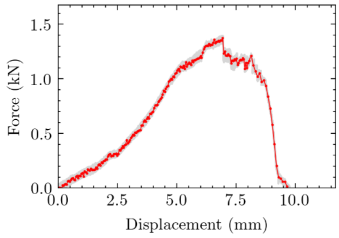


Specimen 3: 3M VHB tape between halves and 3M DP-100 between modules with 3M VHB tape spacers

Failure Mode:
- Flexible and non-catastrophic failure
- Specimen failed due to delamination of adhesive between two halves
- Lower capacity compared to specimens with rigid adhesives

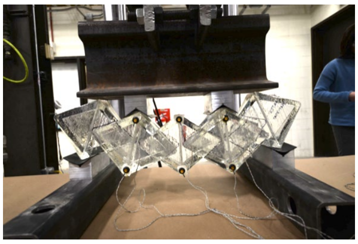


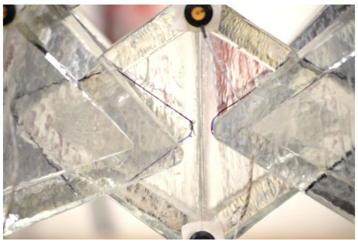


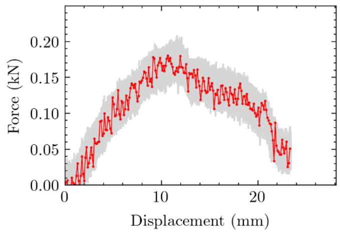


Specimen 4 3M VHB Tape 4910

Failure Mode:
- Flexible and non-catastrophic failure
- Adhesive failed due to very low shear capacity
- Significantly lower capacity compared to samples with rigid adhesives

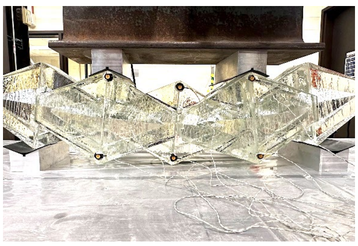


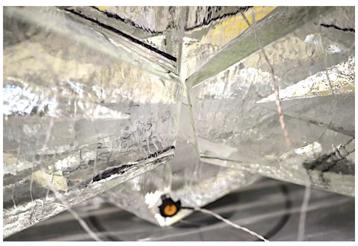




Specimen 5: Dowsil 2400

Failure Mode:
- Flexible and non-catastrophic failure
- Adhesive failed in shear lower capacity compared to rigid adhesives
- Capacity for redistribution of stresses as the adhesive shears between modules





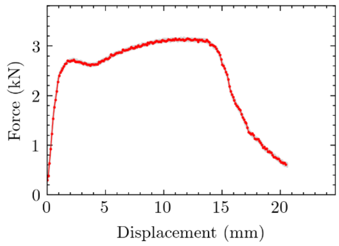


Table 2: 4pt Load Bending tests for an array of adhesive compositions.

The combined results of the 4-point load test for all the specimens are presented in Figure 14.

As indicated by the load-displacement results, the load-bearing capacity of the assembly is significantly influenced by the type of adhesive used for connecting the glass modules and module halves. The load capacity varies across different specimens, ranging from 0.18 kN at 13 mm displacement for Specimen 4, to 22 kN at 3.5 mm displacement for Specimen 2 assembled using 3M DP-100 Plus Clear adhesive with Amnio Saline Pretreatment. This considerable discrepancy underscores the critical importance of adhesive selection for these assemblies. Other crucial factors include the mode of failure. Specimen 2 demonstrates high composite action and rigid behavior at the joints with significant load-bearing capacity. However, it demonstrates low flexibility as it failed when one of the modules cracked through its thickness in the midspan due to the limited capacity for stress redistribution of the rigid adhesive. Similar behavior was observed in Specimen 1, however, the load bearing capacity was about 30% of Specimen 2.

In contrast, other specimens with more flexible adhesive types demonstrate flexible and non-catastrophic failures. As an example, Specimen 5 with Dowsil 2400 demonstrates comparatively lower load bearing capacity (2.7 kN) and mainly failed as the adhesive sheared at the middle joints causing the assembly to bend under load without structural damage to the modules. Specimen 4 showed a similar failure mechanism, however at significantly lower load level which is mainly due to the low shear capacity of the adhesive at the joints across the specimen. Specimen 3, adhered between the modules with a composition of tape spacers and 3M DP-100, failed due to the delamination of the two halves (adhered with 3M Tape) which led to failure of the assembly at relatively low load level without further structural damage to the assembly. Although these failures were less catastrophic, allowing for large deformations without glass detachment, they exhibited significantly lower load-bearing capacity in bending. These test results are very useful to make an appropriate choice of glue based on the expected failure mechanism of the system and very informative in the design process of self-supporting wall systems exposed to lateral environmental loads which can cause out of plane bending in the structure.

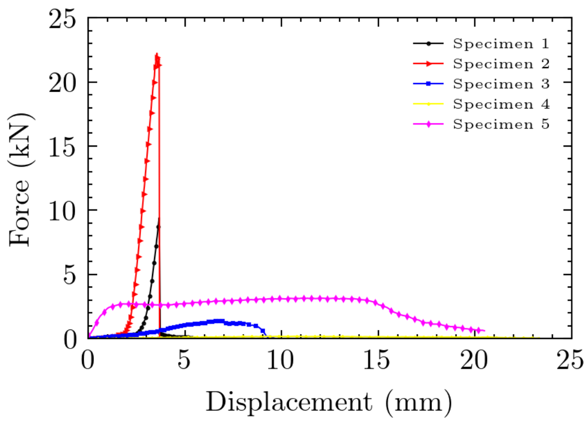


Fig. 14: Force-Displacement diagram for all Specimens described in Table 2.

4.3. Discussion of Results

The test results demonstrate that the type of adhesive significantly impacts the structural behavior and failure mechanism of the proposed cast glass masonry system. Depending on the rigidity of the adhesive, assembly failure can occur due to glass cracking, adhesive failure in shear or debonding, or a combination of both glass and adhesive failure. The results indicate that using more rigid adhesives leads to higher composite action and therefore higher load bearing capacity but may also result in a more brittle failure mechanism. While high composite action with a rigid, monolithic, and reliable structural performance is desirable, it is crucial to consider other structural requirements that influence the choice of adhesive when designing self-supporting wall systems. One of the main requirements is a safe failure mode of the wall system, providing visible warning and retention of glass pieces, allowing sufficient time for evacuation before complete collapse. Another aspect is redundancy and the availability of an alternate load path during partial assembly failure (Green, 2016). As test results indicate, flexible adhesives demonstrate a higher capacity for stress redistribution at locations with stress concentrations, accommodate small relative movements of modules at joints, and have better gap-filling capacity for surface defects. These properties help avoid brittle failure modes and can provide residual capacity after partial failure initiation in the system.

The compressive results show that the proposed assembly gains some redundancy due to its modular nature, as the specimen continued to carry loads after the initial failure of a module in the high-stress location. Additionally, the geometry of *Light Forms* modules introduces an interlocking pattern that enhances the toughness resistance of the assembly. This configuration would benefit from adhesives with some flexible properties to accommodate stress concentrations caused by adjacent bonded module edges.

Furthermore, the overall geometry of the wall assembly can significantly impact the choice of adhesive in terms of strength and flexibility. Large-scale mock-up constructions can test these effects prior to actual construction (Oikonomopoulou et al., 2018). It is also possible to use different adhesive types at various locations within the units and the overall structure based on required behavior. For instance, in intersecting wall systems, different types of adhesives can be employed based on strength and flexibility needs. Applying more flexible adhesives at wall junctions or expansion joints can accommodate relative movements and stress redistributions.

Further structural performance variations include the strategic placement of solid and hollow forms based on the overall load path of a particular configuration.

5. Optical Tests

5.1. Solids and Color: Adhesives as Optical Design Element

Colored film or color-dyed adhesive at the joint between two halves creates an effect that drastically shifts based on the angle of the viewer, predictably darkening the light from some vantage points (Figure 15). When viewing the module directly upon the centerline, the adhesive joint color is nearly imperceptible, however as one moves, the adhesive joint becomes more and more apparent to the point at a 45-degree angle to the centerline of the module, the glass unit appears to entirely take on the color of the adhesive joint.

This offers a striking design opportunity, where the building material can be altered with a placement of color in coordination to optical effects, issues of privacy, and correlation to the programming or use that is housed within the space. Color choice and degree of opacity can also be controlled.

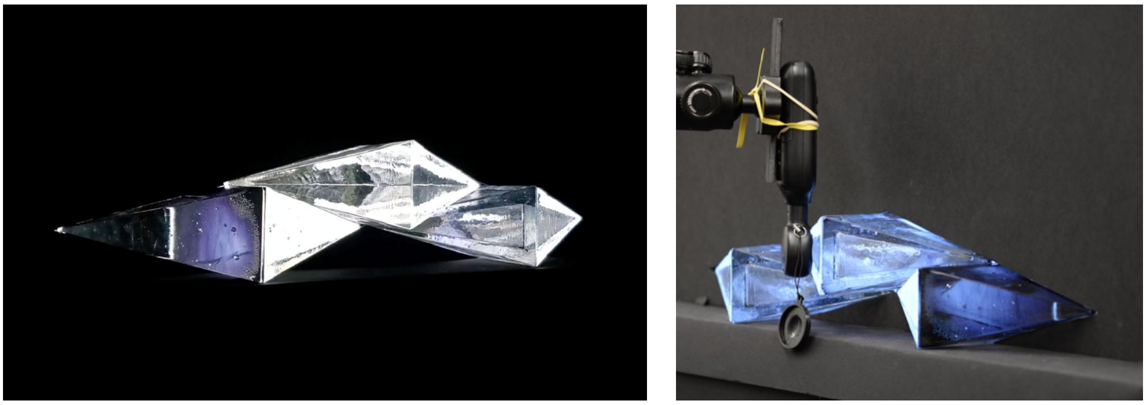


Fig. 15: Color variation induced through dyeing adhesive layer as seen from different angles.

5.2. Optical Shifts within Different Patterns

The polyhedral shape of *Light Forms* creates intricate optical interactions as light travels across its geometrically angled planes and varying thicknesses. Both the 8-sided and 10-sided designs feature faces that may be adjacent or opposite one another, at different angles, and either parallel or non-parallel. Viewing the module as a whole, there is also an intermediate connection between the two halves that influences light refraction. Additionally, internal voids increase the complexity by altering the quantity and angles of the surfaces through which light passes. This results in a complicated relationship between the angles at which light strikes the initial surface and the angle at which it exits. Refraction significantly affects how light appears within each module and the overall system.

A test was conducted with a light meter to measure the amount of light entering solid and voided forms, and after exit at a set of distances beyond the form (0cm, 1cm, 5cm, 10cm, 20cm, 30cm). A control of a flat pane of glass and no glass were also used. Due to the complex relationship of light transmitting through the form, light meter readings were taken perpendicular to the aggregation and normal to the plane face of the module to understand how light refracted and scattered due to the different geometries of the voided or solid modules (Figure 11, 16, 17).

Because of the angles within the forms, some of the units with faceted internal voids demonstrated areas where light was amplified at certain distances, see Figure 17 indicating a focusing of the light. For further analysis, the refraction of light will also be simulated digitally, see section 6 below.

Within these optical tests, *Light Forms* modules with a smoky blue coloured adhesive joint (Figure 15) were tested side by side with modules with transparent adhesive joints between the two halves. In both orientations of light meter readings, the blue adhesive joint modules exhibited a lower transmittance of light (Figure 16, 17).

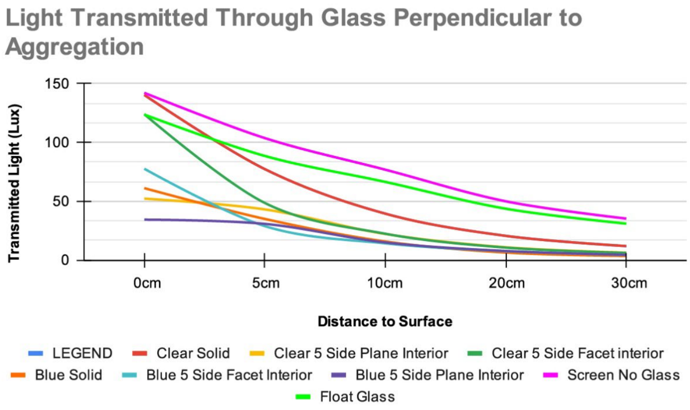


Fig. 16: Light transmission study, with light meter held perpendicular to test aggregation. See Figure 11.

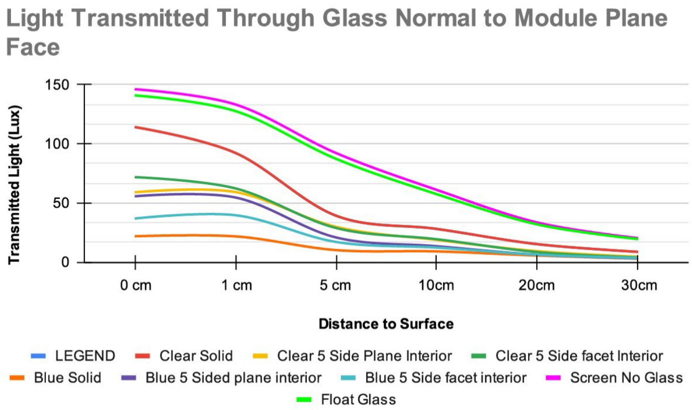


Fig. 17: Light transmission study, with light meter held normal to module plane. See Figure 11.

6. Future Tests

Structural and optical performance have driven design considerations and testing thus far. Those tests will continue as the modules move into industrial production.

Future tests include the following:

- Acoustics: Given the multiple angles of variation in the facets of all the tessellation patterns, it can be inferred that the geometry of the wall will work in an acoustically diffusive manner. At the same time, the system is also a very flat and hard material, capable of reflecting sounding waves. This combination of geometry and glass warrants acoustic tests specific to the performance of each tessellation pattern (Newell, 2022).
- Light Refraction: Refraction of light within the geometries of the *Light Form* modules will be analysed using digital simulation, inputting the refraction index of soda lime glass. Assessment will be conducted on the interior voids, variation in patterns based on orientation, and comparisons across symmetrical and asymmetrical voids.
- R-Value: The thickness of the glass and the sealed pocket of air within the module are two key factors determining the thermal performance of the *Light Forms* modules. Tessellation patterns and orientations influence the R-value with respect to relative thickness of cross section. Future tests will review the thermal qualities of the system and compare solid forms to those with internal volumes regarding R-value.

- Fusing of halves during press casting process or using a low temperature glass enamel: Conventionally, glass blocks produced through industrial glass pressing hot fuse two halves together before annealing to room temperature. During initial hand line press casting of *Light Forms*, there will be testing to see if this is a feasible way to join two halves without the use of adhesive. Also, there will be tests to understand the potential of using low temperature glass enamel to join the two halves.
- Weathering of adhesives: Initial tests have begun to evaluate the weathering of adhesives within the system and the presence of hydration creep into the internal voids. While visual inspection is not indicating the collection of condensation, the next step is to insert a wireless sensor in the void for accurate moisture reads within a physically simulated weather chamber with the Dowsil 2400.

The next spatial step within the research is to construct small freestanding structures that take advantage of the design opportunities and constraints discussed above. *Inhabiting Light*- an outdoor alcove at the University of Michigan Nichols Arboretum will be constructed in 2025 as a space for reflection, introspection, and grief, created from *Light Form* tessellations. Dedicated to care and reflection, the *Inhabiting Light* installation will create a space for rest and privacy as a powerful spatial moment of pause and healing.

These constructions will progressively move up in scale with the goal of completely free standing small weathertight inhabitable structures.

7. Conclusion

Light Forms introduces a significant advancement in the use of glass for architectural applications, focusing on enhancing occupant well-being through natural light modulation and offering creative structural possibilities. This system builds upon existing research on structural cast glass blocks through integrating two halved components into a singular modular unit utilising the constraints and opportunities of press casting processes, allowing for solid and voided variations. Through adhesive testing, Dowsil 2400 exhibits the most desirable qualities for adhesion between courses, while further testing is needed to determine ideal adhesion between module halves. The resulting design creates unique prismatic effects, controlling light and privacy, and introducing color shifts with dyed adhesive joints. The crystalline design of the modular units facilitates variable tessellation patterns, enabling architects to craft spaces with distinct visual and structural characteristics that will be tested in the forthcoming *Inhabiting Light* structure.

By exploring the intersection of geometry, light transmission, and structural performance, *Light Forms* contributes to the field of architectural design by providing versatile, aesthetically appealing, and structural glass modular systems that can be adapted to various architectural needs and translate the natural environment around us.

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