INTRODUCTION:

Throughout human history, the ubiquitous implementation of shell structures has traditionally incoporated labor intensive and time consuming standards of masonry production and construction resulting in structures with limited geometries, programmatic possibilities, responsive natures, and adaptabilities. Traditional masonry thin shells are advantageous in that they are capable of long distances using the least amount of materials. However, they suffer from the limitations of standardized materials, the need for reinforcement, geometry, porosity, and a lack of quality control during the construction process. Similar to thin shells, grid shell structures are also able to achieve great spans with minimal material but also allow for more possibilities for porosity. It is limited in that they cannot provide shelter as they are only frames. The internal forces are carried by members and there must follow a restricted path. The overall research objective is to produce adaptive shell structures with diverse, anisotropic performance by optimizing geometries and patterns of tessellated structural modules through a hybridization of thin and grid shell structures. The resulting shell structures will be anisotropic in nature by using the smallest number of modules to produce the greatest variety of customization within the greatest number of precast concrete components.

TRADITIONAL MASONRY VAULTING

A Vault is an architectural form for an arched form used to provide a space with a ceiling or roof. The simplest kind of vault is the single vault also called a barrel or tunnel vault which is generally semicircular in shape. The barrel vault is a continuous arch, the length being greater than its diameter. As in building an arch, a temporary support is needed while rings of voussoirs are constructed and the rings placed in position. Until the topmost voussoir, the keystones, is positioned, the vault is not self-supporting.

THIN SHELL (ISOTROPIC)

A thin shell is defined as a shell with a thickness which is small compared to its other dimensions, typically at minimal 1:200. The load carrying behavior is determined by the geometry of the form, supports, and the nature of the applied load. The structures are capable of spanning large distances with minimal materials.

GRID SHELL

A grid shell is defined as a structure with the shape and strength of a double curvature shell, but made of a grid instead of a solid surface. A long span structure composed of a network of members creating the single layer grid that forms the curved surface shell. Unlike the thin shell, the loads are carried by members and therefore have to follow a restricted number of paths. Grid shells can be used to reduce the weight of the structure, offer better lighting conditions, or add aesthetics. Grid shells can be considere both as a structure and a facade.

COMPUTATIONAL ANISOTROPIC PRECAST CONCRETE SHELLS

The hybridization of Thin Shell Masonry and Grid Shell structures.
CONTExTUAL PERFORMANCE:

- Stadium
- Building components
- Pavilions
- Facades
- Churches
- Airports
- Exhibition Halls

PRECEDENTS:

THIN SHELL

Gaudí's trencadís vaulting

Gaudí's trencadís vaulting relies on the adhesion of two to three layers of overlapping tiles which are woven together with fast-setting mortar. This method allows for quick construction, less scaffolding, and fewer materials and cost of construction. The tiles are layered at different orientations, giving the assembly strength. The first layer is set with a quick setting adhesive and the rest of the layers are set with regular mortar. Gaudí's trencadís vaulting can generally be done with tiles or no formwork.

César de Céspedes Bus Station:

The building utilizes concrete as the principal material for all elements of the building. The most distinctive feature of the project is the curve of the concrete facing on its outside, which is the result of a concave geometry and reads as a subject in the overall unity of the project. It is a part of a conceptual design but also a functional feature of the bus terminus.

MUK Jr. Park Stone Vault:

Recent developments for the computer-aided fabrication of individual stone blocks of a free form masonry vault in Austin, TX. Based on structural requirements, states of the art & scale, stone cutting processes and software solutions used in the stone industry, new methods were developed to optimize the rock geometry and machine strategies for this structure. A customized software program was written to simplify the process, reduce machine time and extend known fabrication procedures in a reliable and streamlined setup.

Comparison of the traditional stone vault

a. Traditional stone vault
b. Gaudí's trencadís vault

GRID SHELL

Pallazoetto dello Sport:

The dome of the stadium is actually a thin-shell but uses a ribbed system similar to a grid shell structure as the supporting structure. The design was a result of simple geometry and fabrication methods. Rhomboid hollow flat blocks were prefabricated and spread out over the ribbed form.

Presbi Pavilion:

The Presbi pavilion is a compression-only precast concrete vault designed and built in 11 by a student group in dialogue with engineers as a thesis award research project. The structure was first assembled in a gallery space at the Antwerp School of Architecture, then dismantled and reassembled in less than a day (on site) at the Antwerp Festival.

Concrete Gridshell Pavilion:

The form was generated through custom written dynamic relaxation software and fabricated through a combination of CNC machines and casting. The component design was assembled and assembled together, forming a gridshell.

MATERIAL PROPERTIES FOR HYDRO-STONE

Description

Hydrostone is one of the hardest and strongest of all gypsum composites. It is typically recommended for producing high-quality novelty and stationary casting requiring extremely hard surfaces. This product is self-leveling when poured and not suitable for hollow cast applications. Hydrostone must be mechanically mixed for best results and is a high-water absorption resistance material.

COMPOSITION OF INGREDIENTS

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>WT%</th>
<th>TVL (mg/mL)</th>
<th>PEL (mg/mL)</th>
<th>CAS NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster of Paris (CaSO₄•½H₂O)</td>
<td>&gt;85</td>
<td>10</td>
<td>15 (15)%</td>
<td>26468-65-0</td>
</tr>
<tr>
<td>Portland Cement</td>
<td>&lt;10</td>
<td>0.06(R)</td>
<td>1.97(C)</td>
<td>65987-15-1</td>
</tr>
<tr>
<td>Crystalline Silica</td>
<td>&lt;5</td>
<td></td>
<td>0.1(R)</td>
<td>1480360</td>
</tr>
</tbody>
</table>

Physical Properties

- Normal consistency (100 lbs. product) 32
- Hand Mix Weight (lbs. Target: 200 lbs.) 203.8
- Compressive Strength: One hour after set (psi) 4,000
- Compressive Strength: Dry (psi) 10,000
- Density, Wet (lbs./cu. ft.) 119.0
- Density, Dry (lbs./cu. ft.) 128.0
- Moisture Expansion 0.24%
GRASSHOPPER DEFINITION PROBLEM

COMPARATIVE TILE LAYER ADJACENCIES IN SECTION

Although previous grasshopper definition successfully demonstrates a capacity to produce faceted single-layer vaults, it left the following unresolved issues:

1. MULTIPLE STRUCTURAL LAYERS
2. LAYER RETENTION
3. TILES WITH CURVILINEAR FACES
4. HARMONIC CORRESPONDENCE BETWEEN ADJACENT LAYERS

Unrestricted consistent spacing between all three layers of curved tile geometry applied to a reference surface on the newly created grasshopper definition.

Layers of faceted tile with inconsistent spacing between each other resulting from the first grasshopper definition.

Consistent spacing between all three layers of curved tile geometry applied to a reference surface.

LAYER VARIABLES

DETAIL SECTIONS OF THE THREE VAULTS

SOLVING FOR THIN SHELL

TILE COMPARISON

COPLANAR TILES

NEW GRASSHOPPER DEFINITION TO INTEGRATE LAYERING AND ROTATION

APPLICATION OF THE THREE LAYERS ON THE CYCLICAL VAULT

LAYER ONE

LAYER TWO ROTATED AT 90 DEGREES ANGLE

LAYER THREE

TRADITIONAL VAULT

1/2" TILES

1/4" TILES with a 1/16" mortar gap

5/8" TILES with a 1/16" mortar gap

The three layered vault should have a larger compressive strength.
FABRICATION PROCESS
TESTING METHODS

Based on the research by the Polytechnic University of Catalonia with collaboration of other research teams in MIT and ETH on the structural analysis of tile-vaulting methods and varieties specifically the Guastavino vaulting.

A research team attempted to investigate the suitability of the analytical method used and to evaluate the contribution of the selected variables of the stability of the vault and compare the two results.

Philippe Block and John Ochterendorf have developed Thrust Network Analysis (equilibrium analysis method in three dimensions), it is a new methodology for generating compression-only vaulted surfaces and networks which allow designing forms using the minimum compressive material.

The Catalan Vault

The research aims to quantify the contribution of resistance and or balance of the elements that determine the bearing capacity of the tile vault as shape, span, thickness and the existence of spandrel walls.

Jose Luis González, one of the leading specialists in restoration of Catalan vaults recommends load testing as the most reliable method to test its strength.

Uniform testing results are obtained by the application of sand bags which transfers the load uniformly. The variation in the results can naturally vary depending on the type of mesh or tile element used according to López and Rodríguez in the "Guastavino Vaulting".

Pau Roca, an engineer from Barcelona also recommends limit analysis and macromodulation:
- A precise macromodulation of the geometry has to be made.
- Consider the material non-linear.
- Consider limited compressive strength.
- Possible consideration of tangle non-zero (but very limited).
- Consider geometric non-linearity.

INDUSTRY STANDARDS

Some of the most important variables for testing are the uniformed load distribution, eccentric loads and finally the combination of those two. Internal calculations are compared to model testing though the application of an evenly distributed weight and compared to the software calculations. The type of analysis can provide quantitative information, identifying high-compression points or associating tension to cracks or fissures.

The vaults Fig. 1 & 2 have a span of 9.64m and a width of 0.39m. The different parameters are: thickness (2 or 3 layers), the existence of spandrel walls and the height 7.87m or 11.87m.

Load variable:
- Uniform load
- Eccentric load
- Uniform + eccentric load.

TESTING DATA OUTPUT (Cycloidal Vault)

<table>
<thead>
<tr>
<th>Table 1: Quantity and weight of masonry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vault surface area</td>
</tr>
<tr>
<td>Vault thickness (1-3 layers)</td>
</tr>
<tr>
<td>Tile dimensions; unit weight:</td>
</tr>
<tr>
<td>Quantity</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Mortar</td>
</tr>
<tr>
<td>Quantity</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Total weight of vault</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2: Quantity and weight of formwork</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (units weight)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3: Estimate of labor for tile laying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average vault construction crew</td>
</tr>
<tr>
<td>Total duration of tile laying</td>
</tr>
<tr>
<td>First layer</td>
</tr>
<tr>
<td>Second layer</td>
</tr>
<tr>
<td>Third layer</td>
</tr>
<tr>
<td>Estimate labor for tile laying</td>
</tr>
<tr>
<td>Estimate labor for masonry</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4: Structural load testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application of load (sand bags)</td>
</tr>
<tr>
<td>Total weight applied</td>
</tr>
</tbody>
</table>

TESTING PROCEDURES

Testing for strength based on layering methodology that adheres to the Thin Shell definition (minimum of 1.20x).

Dimensions of vault: 4 ft x 4 ft
- Variation in Thickness: 1 Layer
- Layering
  - Pattern variation
- Different materiality in layering

Structural Load Testing

Vault 1 assembly

Vault 2 assembly
DOMES INITIATION AND PROCESS

Research agenda is to investigate and explore using thin shell and grid shell on a different surface geometry such as a dome through computational design. By applying similar techniques as with the cycloidal vaults and with the Guastavino layering system allowing for a solid and porous dome exploration that maintains a higher degree of compressive strength.

STRUCTURAL INTUITIVE DIRECTIVES

- Minimize irregularities
- Maximize centroid coordination
- Maximize layer to layer consistency
- Stabilize printing and geometry

OCULUS & SURFACE ISSUES

The geometrical issue that arose during the digital computation process was to design a thin curved tile for the surface of a dome. A control in the cohesiveness of the tiles was necessary due to the uniformity of the tile pieces, where the oculus becomes most challenging as the geometry becomes infinitely small and control of the tiles is lost.

POROSITY

Introduction and control of porosity through a choreography in the apertures that can become spatially receptive and morphologically exciting.

Form finding and use of the hexagonal pattern along with the diagrid created a matched surface to stabilize and reinforce the structure. A diagrid is a rigid framework given its inherent geometry which by virtue becomes a firm base for the application of layers and a strong geometry form.

In conclusion a tile mating system was created to solve for surface issues in the geometry of a half-circle by creating two geometries that allowed for porosity and layering using digital computation. This allows a solution in the geometry of the oculus by developing prototypes that explore and test the geometry to achieve a greater structural strength with a minimal amount of pieces with a control in variation in thickness of tiles and its center.

DIGITAL COMPUTATION

TILE SIZE AND AMOUNT CONTROL

APERTURE SIZE CONTROL
DOME PROTOTYPES

1. FIRST PROTOTYPES

Attempt to align the geometry tile centers. First prototypes only align at center lines.

2. SECOND VERSION

Change in tile size in accordance to layer row with improved control over tile alignment.

3. THIRD VERSION

Rotation of the second layer from P1 to P2

Solving by applying two different geometrical surfaces with a higher control in alignment and porosity.

LAYERS

Top Layer

Bottom Layer

CRITERIA

STRUCTURAL INTUITIVE DIRECTIVES
- MINIMIZE REGULARITIES
- MAXIMIZE CONTROL COORDINATION
- MAXIMIZE LAYER TO LAYER CONSISTENCY IN PROFILE GEOMETRY

OCULUS OVERLAY
- TILE GEOMETRY STABILITY
- POROSITY
- MINIMAL PARTS

A matted effect is created by layering and the juxtaposition of two different vectors which allows for a more rigid structure with a higher compressive strength while maintaining the thin shell definition and spanning greater distances as a self sustaining structure.
FINAL DOME

Prototype 1 demonstrates how the structure is reinforced through the alignment of the mating system with the use of the hexagonal and diamond geometries which reinforce the joints.

Prototype 2 demonstrates how the structure has a stronger reinforcement through the center points of the tetrahedron, which increases the strength of the entire structure.

Total number of pieces created for the first layer: 162
Total number of pieces created for the second layer: 180
Total number of pieces created in total: 342

PROCESS

GRASSHOPPER  3D PRINT  COAT OF EPSON SALT  APPLICATION OF PROTECTIVE GLOSS  CREATE AND ASSEMBLE FORMWORK  BUILD THE FIRST LAYER  BUILD THE SECOND LAYER

PERFORMANCE
ASYMMETRICAL VAULTING

VAULT INITIATION AND PROCESS
Architecture requires diverse solutions given the contextual site requirements that require a range of topological diversity that typically requires asymmetrical solutions. The thin-shell allows the production of these topological variations with enhanced surface performance. The design and shape can be found on the site given the context with the system more efficiently. Efficiency is obtained from using the least amount of material optimized matted system, maximized layer to layer consistency and minimization of irregularities all through digital computation.

PRECEDENT
Analyzing some of the research that has come out of The Block-Research Group (ERG) at the Institute of Technology in Architecture, ETH Zürich. Using similar prototypes and concepts through modern and past research that adequately represents the final stage of the research through the design of asymmetric vault.

DIGITAL COMPUTATION
Creating a layered asymmetrical structure that follows stress and structural optimization to achieve a desirable length with a minimal amount of tiles.

PERFORMANCE
DIGITAL OUTPUT

PERSPECTIVE 1

PERSPECTIVE 3

PERSPECTIVE 2

PLAN OF ASYMMETRICAL VAULT