<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Institution</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>John A. Ochsendorf, PhD</td>
<td>Associate Professor of Building Technology</td>
<td>Massachusetts Institute of Technology</td>
<td>Thesis Supervisor</td>
</tr>
<tr>
<td>Nader Tehrani</td>
<td>Professor of Architecture, Department Head</td>
<td>Massachusetts Institute of Technology</td>
<td>Thesis Supervisor</td>
</tr>
<tr>
<td>Mark Jarzombek, PhD</td>
<td>Professor of the History and Theory of Architecture</td>
<td>Massachusetts Institute of Technology</td>
<td>Thesis Reader</td>
</tr>
</tbody>
</table>
THE 4-DIMENSIONAL MASONRY CONSTRUCTION

Lara K. Davis

Submitted to the Department of Architecture on May 21, 2010
in Partial Fulfillment of the Requirements for the Degree of Master of Architecture at the Massachusetts Institute of Technology

Thesis Supervisor:
John A. Ochsendorf, PhD
Title: Associate Professor of Building Technology

Thesis Supervisor:
Nader Tehrani
Title: Professor of Architecture, Department Head

Abstract

This design-research thesis – The 4-Dimensional Masonry Construction – presents innovation in the design and construction of thin-shell tile vaulted structures.

The core research contributions of this thesis are:

#1 Testing limit states of unit hinging + displacement in single-layer tile vaults.

#2 Introducing modified masonry units to achieve directional surfaces with high degrees of double-curvature and porosity.

The 4-Dimensional Masonry Construction operates as a heuristic device to conceptualize, visualize and represent the way in which a masonry unit hinges in space within a complex, doubly-curved structural surface.

By modifying masonry units, the resulting system of aggregation can produce asymmetrical and disaggregating tile coursing geometries – predictable yet geometrically incomprehensible systems.

By establishing reciprocity between the modified unit/ system relation and the method of vault assembly, new forms in structural masonry are possible. Such structural forms are a product of these unique unit/ system geometries, the constraint of structural geometries (catenary systems and double curvature for lateral stiffness), the techniques of graphical analysis to define such a structure spatially, and the logic of sequencing to maintain the units' systematic relation, to constrain units inherently given to push the limits of constructibility.

Keywords: design-research, structural masonry, construction
Again, it sometimes appears to be thought that the fourth dimensions is in some way different from the three dimensions which we know. But there is nothing mysterious at all about it. It is just an ordinary dimension tilted up in some way, which with our bodily organs we cannot point to. But if it is bent down, it will be just like any ordinary dimension: a line which went up into the fourth dimension one inch will, when bent down, lie an inch in any known direction we like to point out. Only if this line in the fourth dimension be supposed to be connected rigidly with any rigid body, one of the directions in that rigid body must point away in the fourth dimension when the line that was in the fourth dimension comes into a 3 space direction.


Apart from the interest of speculations of this kind they have considerable value: for they enable us to express in intelligible terms things of which we can form no image. They supply us, as it were, with scaffolding, which the mind can make use of in building up its conceptions. And the additional gain to our power of representation is very great.

– Charles Howard Hinton, What is the Fourth Dimension, 1886.
THE 4-DIMENSIONAL MASONRY CONSTRUCTION
ACKNOWLEDGEMENTS:
First and foremost, I would like to express my tremendous gratitude to my thesis advisory committee, co-advisors Professor John Ochsendorf and Nader Tehrani, and reader Mark Jarzombek. I believe quite honestly that these three have comprised a committee of the highest degree – across the terrains of structural engineering, design and history/theory – that I have seen in my time at MIT. John, most of all, has provided me with opportunities beyond my expectations and has assisted me a very great deal in the realization of my work. For the first inertia in the formulation of this thesis, the scholar Yonca Hüröl at Eastern Mediterranean University in Cyprus was especially supportive, and I would like to consider her as my honorary and silent reader.

For their role in the Cooper-Hewitt vault design and construction, I am indebted to John Ochsendorf and the MIT Masonry Research Group, our installation crew at the Cooper-Hewitt, and project manager Mallory Taub. I am also grateful to Cooper-Hewitt production manager Matt O’Connor and his staff, especially Kevin and Roy. James Kolodziey, Mr. Charles Taylor, and Steve Blankenbeker have contributed enormous time, support, and clay science research knowledge, in addition to the donation of their stunning ‘****’-bricks. I hope to return their contribution ten-fold.

I am thankful for the generous support of the Marvin E. Goody scholarship, selection committee, and recommenders John Ochsendorf and Larry Sass. I owe my gratitude to the following individuals: Philippe Block, who allowed me generously to re-build a model, for which the pieces are ever shifting into place. Michael Ramage, for his many advices – in whose ‘footings’ I follow! The Terrescope group, whose low-carbon research and creative initiative was inspiring and informative. Jim Harrington for his support and trust in allowing me to build my thesis vault prototype. Duncan Kincaid, for printing support and the most wickedly sharp humor and intellect in the most stressful of final production moments. Thesis helpers Mallory Taub, Samar Malek, Runo Okiomah, Alex Atwood, MarissaGrace Desmond, and Marissa Cheng – without the support of these people, the final presentation would have been a shadow of what it was. The ghosts, invisible laborers, and the greatest critics without whom this also would not have come to pass – at least, in any case, not without the meaning it now has. Mark Goulthorpe, for refusing to accept my limitations.

These years have been ones in which only the greatest and most challenging travels within have been the path through which – to draw. My deepest gratitude goes to Mary Fillman, Larry Sass, Monique Buzzarté, Deneene Whitehead and Pamela Hawkins, for their unending support, friendship and perspective. I must thank more than all my family, Barbara, Wayne, Shana and Sara, especially my Mom; without their faith in me, I would surely not have made it through. The strength from the continuity in my family’s work – especially quilter Grandma Elizabeth Baird and geologist Papa Baird – has been enduring. And Sara, who has watched me lay every brick, disassemble every wall, and still build again – masonry and biology, Ras. Last, to Ak-bak, who carried me all the way here and through, and Mallory, who saw that I finish it – I could not have done this without you.

LKD
May 2010
TABLE OF CONTENTS:
# Table of Contents

I. Introduction ......................................................................................................................... 11
   1. Thesis, Research & Methodology statements ............................................................... 12
   2. Benchmarks ...................................................................................................................... 15
      2.1 Economy of Form ...................................................................................................... 16
      2.2 Economy of Material ............................................................................................... 18
   3. Platforms for masonry innovation .................................................................................. 21
      3.1 System/ Unit Logic (Systems Aggregation) ............................................................... 22
      3.2 Method of Assembly (4-Dimensional Drawing) ........................................................ 24

II. Construction Analysis ........................................................................................................ 27

III. Applied Research: Innovation from Construction .............................................................. 41

IV. Design-Research Synthesis: 4 Dimensional Constructional Design ..................................... 49

V. Appendix ........................................................................................................................... 79
   7. BLOG Discourse: 4D Masonry Construction (selected) ................................................... 81
   8. BLOG Discourse: MIT Masonry Research Group (selected) ........................................... 97
   9. Materials research .......................................................................................................... 113
      9.1 Green Thin-Brick: Sustainable brick technologies and materials ................................. 114
      9.2 Mortar testing .......................................................................................................... 118
   10. MIT Facilities submission ............................................................................................. 122
   11. Marvin E. Goody prize statement ................................................................................... 128

VI. Bibliography ...................................................................................................................... 132

VII. Illustration Credits ............................................................................................................ 134
INTRODUCTION:
RESEARCH CONTRIBUTIONS

#1 TESTING LIMIT STATES OF HINGING + ROTATION IN SINGLE LAYER TILE VAULTS

#2 INTRODUCING MODIFIED MASONRY UNITS TO ACHIEVE A DIRECTIONAL SURFACE WITH HIGH DEGREES OF DOUBLE-CURVATURE AND POROSITY

SPATIAL DRAWING TOOLS:

- Chain
- Mason's Line
- Cintrel
- Plumb
- Level
- Line Level
- Template
- Compass
- Angle
- Rule
The 4-Dimensional Masonry Construction is a heuristic device to conceptualize, visualize and represent the way in which a masonry unit hinges in space within a complex, doubly-curved surface. Such is the mental construction of the mason for predictable and controlled geometries; however, this technique may also be applied to predictable but geometrically incomprehensible systems.

The skills of the mason may be qualified as 4-dimensional insofar as they are time-based constructional logics. The act of construction in masonry requires an assessment of error in time as masonry units are laid. The mason must 'see the surface' as it is deployed and anticipate its behavior to correct imminent errors in coursing pattern and in-situ structural stability. Both of these categories of error are critical and unique to masonry construction, since masonry structures are unstable until fully completed, and unit masonry must be corrected for error continually throughout construction to keep many small errors from cascading. The use of registration lines and formwork are the drawn spatial lines which must serve as guides for the reciprocal relationship between masonry unit and masonry system.

Through an analytical approach to the learned skills of the mason, constructional logics may be identified and re-synthesized towards innovative design logics, flipping the valence of a synthetic space-sense and logic of error correction into a methodology for design. While a construction produced by the mason's methods may already be considered as a 4-dimensional drawing – or construction as an act of spatial drawing in time – the very lines and rules which define good craftsmanship may be transgressed to draw – thus to build – an apparently impossible structure.
BENCHMARKS:
This research in structural masonry rests firmly on the foundations of modern innovation in the area of thin-shell structural form. Early and mid-20th century architect-engineer-builders such as Antoni Gaudí, Rafael Guastavino, Eladio Dieste and Félix Candela have demonstrated the tremendous invention possible in thin-shell vault construction through the use of catenary structural principles. It is by working within the very tight constraints of structural form-finding that these architects have pioneered the field of contemporary structural thin-shell innovation, but just as importantly, pioneered critical practices of material economy. These so-called 'minimum material forms' are likewise the product of a long history of discovery in the structural behavior of masonry. It is by utilizing these dual design-goals—structural efficiency and formal innovation—that the thesis proposes to make its case.

It is additionally important to note that innovation such as this would not have been possible without the aid of the structural drawing techniques of graphical analysis. Such drawing techniques served, however, not only as the tool for structural form-finding, but also as a comprehensive methodology in coordinating constructional logics. The graphical funicular drawing—which translates between engineering constraints and masonry form—can be conceived of beyond the two dimensions of the traditional design drawing, to be translated directly into the constructional rules for generating a masonry surface, formwork strategy, and thus a sequenced, 4-dimensional construction strategy.
This thesis proposes to radicalize concerns of ‘economy of form’ by subverting the linear structure of material consumption. The masonry unit will not be taken as given in either form or material, but rather considered as a unit which inflects a broader system of aggregation and a resource which inflects a broader system of material consumption and reuse. By taking on the time-based, 4-dimensional perhaps, considerations of industrial brick production – with its association to a ‘cradle to gate’ economy – the thesis proposes an alternative material economy by tapping material waste flows. Current paradigms of ‘cradle to cradle’ design often elevate the post-consumer ‘item’ to the status of aggregation – i.e. bottles, cups, and tires stacked systematically to generate a composite masonry system. The most critical outcome of this one-to-one translation is the notion that material properties impact the structural behavior of the system, that trash performs somehow differently than virgin resources by virtue of its ‘used’ or ‘weakened’ state. If this same critia of judgment, however, is applied to research at the level of material science – in this case, clay brick production – then re-constituted waste materials may be assessed for their performance in the production of a re-constituted brick. The brick material which was used in the vault construction at the Cooper-Hewitt Museum as well as in the final thesis construction, Green Leaf Brick, is a 100% post-consumer and post-industrial recycled product, composed of approximately 30% processed sewage wastes. The material science which went into the engineering of this brick well demonstrates the argument of radical material economy put forth by the thesis, insofar as the clay-body of the Green Leaf brick produces a more structurally robust brick through its consideration of material behavior. In other words, this brick is not simply radical because it is made of 30% shit – but radical because the processed sewage waste, when used in combination with other recycled materials, has a material performance which rivals the best brick in the industry.
## Green Leaf Brick

**Recycled Content:**

<table>
<thead>
<tr>
<th>30%</th>
<th>Processed Sewage Wastes</th>
<th>Glassifying</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>Recycled Iron Oxides</td>
<td>Clay-body Plasticity</td>
</tr>
<tr>
<td></td>
<td>Mineral Tailings</td>
<td>Increased Comp. Strength</td>
</tr>
<tr>
<td></td>
<td>Open Pit Mining By-Products</td>
<td>Grog: Rapid Drying/Firing</td>
</tr>
<tr>
<td></td>
<td>Industrial Starches</td>
<td>Glassifying</td>
</tr>
<tr>
<td></td>
<td>Virgin Ceramic Scrap</td>
<td>Increased Plasticity</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>Pure Silica</td>
</tr>
<tr>
<td></td>
<td>Plant Refuse (Organics)</td>
<td>Grog: Rapid Drying/Firing</td>
</tr>
<tr>
<td></td>
<td>Dust from Air Filtration Units</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Misc. Landfill Ceramics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(i.e. Ceramic Toilets)</td>
<td></td>
</tr>
</tbody>
</table>

**Effect on Clay Body:**

- Glassifying
- Clay-body plasticity
- Increased comp. strength
- Grog: rapid drying/firing
- Increased plasticity
- Pure silica
- Grog: rapid drying/firing

---

**Aggregated Refuse**

- Sugei San, Hanover, PA
- Rural Studio, Yancey Chapel
- Gregory Dick, Hanover Pavilion
PLATFORMS FOR INNOVATION:
AGGREGATIVE SYSTEMS ::
THRESHOLDS OF HINGING IN THIN-SHELL MASONRY

The 4-Dimensional Masonry Construction takes the position that constructional logics learned through the act of construction – specifically with respect to unit/system relationships and hinging in thin-shell masonry structures – may be abstracted, synthesized and applied towards the design of innovative masonry structures.

The precedents for this investigation of limit-states in masonry aggregation – largely computational, as in the work of Gramazio and Kohler – all address corbelled units and not hinging between units. Additionally, such work also typically fails to generate a synthetic strategy for structural limits or constructional criteria. The greatest departure of this thesis from the methods of contemporary, computational masonry innovation is that logics of the hand are being reconciled towards design objectives – a strategy which is perhaps uncommon in a contemporary context fascinated with computational geometry, yet which lacks sufficient parameters for effective translation into material form.

The time-based act of construction may inform a series of constructional logics and constraints, which may then be abstracted and re-applied. Material, tectonic, human, structural and sequential errors – the natural tendencies of masonry aggregation towards a state of dis-aggregation, which can be learned only through direct knowledge in constructional testing – may be utilized as tools towards new paradigms of masonry design. These constructional logics can then enable masonry design at the very limit-state of what is possible for masonry – creating an apparently impossible structure, which nevertheless is determined by critical rules.
All of these precedents involve what might be called "construction as an act of spatial drawing"—or 4-dimensional drawing. Through the use of spatial drawing tools for masonry—such as the chain, mason’s line, plumb, level, line-level, template (paper or wood trait), compass or dividers, rule, angle, and cintrel—a comprehensive system is put in place for constructibility, critical sequencing, accurate projection from 2-dimensional drawing to 3-dimensional space, and registration for complex unit/system relations (or masonry systems with non-uniform units).

Such non-uniform units and the associated systems of translational, 4-dimensional drawing are typified by stone stereotomy. It may be conceptualized as 4-dimensional insofar as the construction of the stereometric trait involves the temporal operative of rotation, revetment and development. In one drawing, the procedural translation is legible: one two-dimensional drawing becomes descriptive and technically enables a translation into an incomprehensible spatial geometry. (For further discussion, see Robin Evans’ "The Projective Cast", particularly the chapter entitled “Drawn Stone”)

Nevertheless, no such precedents of this 4-dimensional drawing pertain to brick masonry, typically a system comprised of uniform units. This thesis investigates the re-design of the brick unit itself, introducing simple modified brick units and a hybridized form of stereotomy for industrial production. By reinserting concerns of construction sequence (already critical in the construction of masonry structures), the brick unit and its system of registration can be re-considered in a 4-dimensional translation, which enables geometrical, structural and surface aspect qualities not previously possible in brick.
CONSTRUCTION ANALYSIS:
4D CONSTRUCTIONAL ANALYSIS
THE COOPER-HEWITT PROTOTYPE, January 2010
EXTRACTING CONSTRUCTIONAL RULES:

The following analysis has been extracted from the process of building the first prototype of two identical vaults, designed by the MIT Masonry Research Group and built in January of 2010. I served as a primary designer and construction manager for this project. By carefully observing discrepancies between predicted, designed vaults and errors which are produced during construction, constructional rules may be abstracted from learned experience.

The formative structural design parameters of this vault include: 1. A series of longitudinal catenary lines embedded in the masonry surface as the primary structural system. 2. A series of transverse splines, which are fixed in length to maintain equal masonry coursing (and to minimize comprehensive custom-cutting), but which vary in curvature to generate an undulating masonry surface with a deep structural footprint and stiffening double-curvature.

An analysis of the vault may be broken down into the rules of form and the rules of sequencing. For the former, the above description will suffice. The following drawn analysis will predominantly address the rules of sequencing, as they pertain to the observation of structural integrity in in-situ transitional construction states and human error in the process of sequentially laying bricks. These two categories of sequencing are critical and unique to the domain of structural masonry construction, without which a thin-shell vault can very rapidly fail to maintain a viable unit/system relationship, and subsequently, a viable structural form.
IN-SITU STRUCTURAL STABILITY

GRAPHICAL EQUILIBRIUM ANALYSIS
CASCADING HUMAN ERROR
UNIT CONSTRAINTS :: TURNING RADIUS
HINGING :: SHORT AND LONG AXIS

 UNIT-SYSTEM BRICK OPERATIONS:

 SHORT AXIS HINGE
 LONG AXIS HINGE
 SHORT + LONG AXIS HINGE
 SHORT EDGE DISPLACEMENT
 LONG EDGE DISPLACEMENT
 SHORT + LONG EDGE DISPLACEMENT
MULTI-AXIS HINGING:

A + B
APPLIED RESEARCH:
An extreme increase of the thickness of brick used to build Vault 201 at the Cooper-Hewitt Museum meant that a new strategy entered had to be developed to build the surface. The analytical component of the thesis – in addition to the experience of comprehensive custom-cutting in the prototype vault built in January – indicated that our vault’s high degree of double-curvature would have too great a turning radius for this brick to accommodate without destroying the structural coherency of the surface. Thus, a small taxonomy of modified bricks was developed – three primitives: a long-end bevel, short-end bevel, and a short-end oblique – which, when two or more were combined, would require a chiral position in the vault. As the construction manager for this installation, it was my responsibility to solve this challenge ahead of time, to build and to direct the construction of this vault with custom orders of modified units. Any of these modifications, however, could have been industrially produced through typical industry clay extruders. This discovery, born out of material constraints and constructional logics, would indicate for later design implementation the ways in which a modified unit can be made to achieve strategically directional surfaces.
THE MODIFIED UNIT ::
HYBRIDIZED STEREOTOMY FOR INDUSTRIAL PRODUCTION

CLAY BLANK
DIE
EXTRUSION

MASSONRY UNIT
(pre-fired)
As we have seen, there are material limits and unit constraints to the degree of curvature possible in doubly-curved masonry vaults, with respect to the relational proportion between the unit size and the overall span of the structure. Double-curvature is nevertheless desirable, because it provides added structural rigidity and a greater effective structural footprint (enhancing both the structural performance of the completed vault but also in in-situ states during construction, before all forces are distributed through the system). We can, however, modify the unit to accommodate for much higher degrees of double-curvature – a strategy which may also be wielded towards new aesthetic terrain in contemporary vault construction.
DESIGN-RESEARCH SYNTHESIS:
SYNTHESIZED 4D MASONRY CONSTRUCTION DESIGN LOGIC
RECIPROCAL LOGIC: UNIT/SYSTEM // METHOD OF ASSEMBLY

UNIT ↔ SYSTEM
DIRECTIONALITY
HINGING
SEQUENCE

METHOD OF ASSEMBLY
REGISTRATION
FORMWORK
(INSTALLATION/CONSTRUCTION/REMOVAL)
BRICK SEQUENCING
BRICK UNIT OPERATION
(HINGING/SLIDING/CUSTOM CUTTING)

FORMWORK
The 4-Dimensional Masonry Construction proposes that the masonry unit is conceptualized, visualized and positioned with respect to a comprehensive strategy which 'registers' it within a complexly hinged system. These registration lines are the 'invisible' construction lines which critically dictate both position and sequence. Since the masonry unit in this case is modified, the geometry of the masonry unit and masonry system are reciprocal. These geometries of masonry coursing, however, are merely concerns of pattern geometry. The more challenging question is how to embed radical pattern geometries from coursing into structural geometries.

The following investigations show how the masonry system is tested in limit-states of both unit hinging and displacement. The thin-shell tile vault is radicalized by allowing the units to operate within a translational geometry, both hinging and displacing within the surface to create vaults with high degrees of double-curvature and porosity. Where the typical unit may be analyzed graphically by virtue of the hinging constraints on a surface, these research discoveries nevertheless fall short of the description of an asymmetrical and displacing unit. To introduce apertures into thin-shell vaults, we must separate the pattern geometries and structural geometries, selecting a masonry system which allows for porosity, whilst still nevertheless allowing for the most efficient transfer of structural loads to the ground. A formwork strategy must then be introduced that allows the modified masonry unit to be deployed consistent with the tendencies of its geometry – in other words, each masonry unit must define its structural position and formwork support conditions, rather than a fixed formwork defining the position of the masonry unit. The units are no longer fixed, but generating directional surfaces. The resulting structures may be conceived of as 2-dimensional coursing or pattern geometries projected into a 3-dimensional structural forms. These unique geometries push the very limits of the structural and constructional constraints in thin-shell tile vaulting, resulting in diaphanous and structurally unique thin-shell vaults, which are nevertheless are rigidly defined by the rules of each.
COURSING PATTERN & REGISTRATION LINES
RELATING UNIT, SYSTEM AND SEQUENCE

PARALLEL

HERRING BONE

DIAGONAL

ALTERNATING

UNDULATING

TAPIRED

FIXED LINE
(PARALLEL)

CHALLENGES OF TAUGHT STRING REGISTRATION:
A: REQUIRES RELIABLE CONNECTIONS (CATENARY - HIGH ABOVE)
B: CANNOT DESCRIBE CURVATURE
C: TIME CONSUMING INSTALLATION
D: REGISTRATION DOES NOT PRODUCE FORMWORK STRATEGY
DRAWING IN SPACE:

1: A REGISTRATION LINE IS A LINE DRAWN IN SPACE BY WHICH TO ALIGN MASONRY UNITS.
2: THIS MUST BE A TAUGHT LINE (STRING SECURED BY ANCHORS OR GRAVITY).
3: IT MUST HAVE SUFFICIENT INFORMATION TO POSITION A UNIT WITH RESPECT TO ITS 'SYSTEM TRANSLATIONS'.
4: UNITS CAN BE REGISTERED PARALLEL OR PERPENDICULAR TO SURFACE (OR BOTH).
5: REG LINES CAN BE TOTALLY INVISIBLE. 
   (IE. A CIRCLE INSCRIBED BY A ROTATING LINE.)

WHAT IF REGISTRATION TECHNIQUE + FORM STRATEGY WERE COINCIDENT?
UNIT CONSTRAINTS :: A 4D GRAPHICAL SOLUTION
PATTERN, POROSITY & DISAGGREGATION :: TRANSLATIONAL GEOMETRIES OF THE UNIT

UNIT TRANSLATIONS

UNIT PROPORTIONS

1. TRANSLATIONAL
2. ROTATIONAL
   - 90° rotation
   - 180° rotation
   - 270° rotation
3. MIRROR REFLECTION
4. GLIDE REFLECTION

STRUCTURAL GEOMETRY

PATTERN GEOMETRY
1: EASIEST SURFACE REGISTRATION = RADIAL SWEEP
   FAST/ SIMPLE/ INEXPENSIVE MATERIAL AND LABOR.

2: HOWEVER, CATENARY FORM IS NOT A FIXED RADIUS.
   GOTHICS APPROXIMATED THIS GEOMETRY WITH A 2 POINT ARCH.

FORMWORK STRATEGY
CATENARY CINTREL

3: THE USE OF RADIAL REGISTRATION SYSTEM FOR CATENARY GEOMETRY.
   LIMITATIONS: SYMMETRICAL DOMICAL GEOMETRIES ONLY.

HOW TO DRAW A NON-UNIFORM OR DOUBLY CURVED SURFACE WITH A CATENARY CINTREL?
4D ASSEMBLY SERIES

1: ESTABLISH VAULT BOUNDARY CONDITIONS & SURFACE POINTS
2: ROTATE TO PLANE SURFACE FOR CATENARY CONSTRUCTION
3: DRAW GRAPHICAL ANALYSIS
   A: DRAW LOAD LINES AT INTERVALS ON FORM
   B: CONSTRUCT CATENARY SEGMENTS
   C: ESTABLISH HEIGHT INTERVALS
4: PLACE 4D FORMWORK REGISTRATION
   A: MATCH CATENARY HEIGHTS
5: ROTATE INTO VERTICAL POSITION
6: JOIN WITH PLATE FOR MASONRY SURFACE

DRAWING IN SPACE ::
WHAT DOES A CONSTRUCTION DRAW THAT A DRAWING CANNOT?
STRUCTURAL INNOVATION:
CONTROL - BARREL VAULT

EXPERIMENTAL - [MODELLED WITHOUT APERTURES]
THE DIRECTIONAL TENDENCY OF BRICK ERROR CASCADE AS AN INTELLIGENT SYSTEM

ORTHOGONAL BRICK

DIRECTIONAL UNIT

SYSTEM DIRECTIONAL TENDENCY

UNIT DIRECTIONAL TENDENCY

SURFACE VECTOR TERMINAL EDGE

RE-DIRECTION OF SURFACE
ANALYSIS OF UNIT CURVATURE

1D
UNIT ALIGNMENT

0°

4°

8°

12°

16°

2D
SYSTEM AGGREGATION :: SEQUENCING
STRATEGY OF PROJECTION:

PROJECTED

UNFOLDED

TENDENCIES OF PATTERN CURVATURE

1D

2D

3D

SPATIAL HINGING
4D CONSTRUCTIONAL DRAWING IN SPACE

1st ← --- → Last
2D SYSTEM VARIATION:

UNIT:
BLOG DISCOURSE:  
4D MASONRY CONSTRUCTION
4D Masonry Tools
April 29, 2010

Can one imagine a compass (or dividers) – the most primary tool of the historical mason – without the dimension of time, without the operative task of the rotation?

FORM IS DICTATED BY 4-DIMENSIONAL DRAWING TECHNIQUE.
April 29, 2010

4D Drawing in Funicular masonry
April 29, 2010

As far as the 4-Dimensional drawing goes, there is a tremendous precedent of such a concept in the history of the design of funicular masonry structures. Graphical analysis itself is a drawing system which is scalable to describe the surface of a built structure, and is further materialized through its foundational principles in Hooke's Second Law:

“As hangs the flexible line, so but inverted will stand the rigid arch.”

So, the funicular form itself – a hyperbolic cosine function delineating the most efficient and minimal form under self-weight – is not easily described by geometrical drawing, but derived instantaneously with a chain – a material proficiency! The word catenary means “relating to a chain”. The German term “Kettenlinie” means literally “chain-line”. So, this formative structural logic for minimal forms in masonry is approximated by a drawing convention – graphical analysis – which may translate between design and construction, yet is most wholly represented by a material line under self-load – a chain.

Thus, the 4-Dimensional Masonry Construction is the relationship and the act of translation between design drawing and material drawing.

Guastavino, Cathedral of St. John the Divine.
What is the 4-Dimensional Drawing?
April 29, 2010

Since one of the 4 research facets of this thesis— and really, the most significant angle of theoretical and technical innovation— is "4D Design: Spatial, Material and Constructional drawing", it is critical here to clarify what is meant by the 4-dimensional drawing.

The 4-dimensional drawing is embedded within the act of construction itself, and is an integral principle of the way in which a masonry structure (as opposed to any other type of construction) is built by craftsmen. Now, all sorts of constructional methods involve a registration of sorts so that building components 'line up' in their fully assembled state. But masonry is particular, insofar as the builder must 'see a surface' through all stages of construction, carefully laying bricks in position so that the geometry of the entire system is not compromised by a poorly placed brick which cascades into system error. This is particularly important when building with techniques derived from Spanish timbrel vaulting, where bricks are set by cantilevering into space off of the last course, and are set very rapidly on account of the use of high compressive strength and rapid-set plaster mortar. When a surface then curves into space (in two directions nonetheless), how does the mason know where each brick should be positioned so that the structural form is not lost?

Many different types of tools are used by the craftsman to 'draw in space' the ideal registration for a masonry surface. Mason's line or chain, plumbs, line-levels, levels, squares, angles, templates (paper, wood, or traits), compass (or dividers) and rule. In a constructional system, certain of these tools may combine with the greatest registration tools of the mason – the hand and the eye – to systematically describe where the masonry surface wants to be in any particular position. One such system is the cintel, a central pole with mason's line connected at the top, which may be rotated about the pole to register bricks in the construction of a dome.

But still – these masonry tools occupy a grey zone between drawing as an act of building and building as an act of drawing.

The board below – long since the desired theme of the 4-Dimensional Masonry Construction – will come to be tested as analytical research, design and construction overlap. These examples – stereometrical drawing, Islamic Mucarnas drawing, and the ruled-surface hyperboloids of Gaudi – are drawing systems which are made to translate into a 3-dimensional space, as registration of masonry surface in the temporal act of construction. Pencil lines on paper become drawings on materials and construction surfaces, extended by the tools of the mason into space. This is the 4-dimensional drawing, a critical translator between masonry design and construction, drawing and building.
Penultimate review
April 26, 2010

From Construction to Design, Design to Construction
April 13, 2010
Intellectual Q’s
March 2, 2010

_ Precisely how are the ‘intellectual’ question and the ‘constructional’ question posed as mutually exclusive?

_ Where do concerns of ‘craft’ lie in relation to contemporary computational design?

_ What is the threshold of computation in the domain of human and material error?

_ What are the implications of the distinction “building a sketch” (as opposed to the “illustration of a geometry”) suggested by Nader, and how does this apply to notions of the 4-dimensional constructive drawing?

_ Can the customized treatment of an industrially produced unit be ascribed to the domain of the craftsman or builder, by virtue of the attention to idiosyncratic details of fixed and predictable systems? Likewise, may the variability of unitized systems be ascribed to the domain of the designer? May one utilize the former in the service of the latter, exploiting this knowledge of the hand towards new applications – not merely fastidious craftsmanship, but crafted design?

_ What might reconcile the apparent incommensurateness of (increasing) complexity in rule-based logics and the synthetic, sensory responsiveness and intuition of contemporary craft? Is design itself not positioned as antithetical to such sensory responsiveness?

_ Can one say that stereotomy was a product of geometric practices associated with renaissance architecture? According to Robin Evans, stereotomy evolved from geometry just as it did from constructibility: Cutting would be thus a geometric and constructional “reciprocity between masonry unit and method of assembly” (Nader). I like this phrase.

_ Is such practical geometry not by nature a reconciliation of geometry and material, theory and praxis?

_ Is it possible for a masonry unit to generate states of in-situ structural stability?

_ There is an Irish word – ‘tomhais’ – which means both ‘guess’ and ‘measure’. Can such a concept be represented by the intuitive measuring and accounting of the craftsman? How can an intuitive accounting – synthesized knowledge of the hand, the eye, the body – come to be analytically represented through such a system as reductive computational analysis? How can this intelligence be extracted in application to a computational ‘craftsmanship’, a synthetic and analytic constructive sensibility?

_ What are the limits of analytical methodologies in computational programming?
Is the greatest weakness of computation that it considers all things as rule based logics, where rule-based logics have an inherent limit to the number of variables or parameters to maintain the coherency of a problem? Can sensory responsive logics of craftsmanship intuitively synthesize a great many more variables?

Does 'computational determinacy' exclude the reconciliation between what may be computationally generated and how it is resolved in construction?

Is most computational design motivated by a desire for the transcendence of the concerns of labor (ie. Gramazio + Kohler, Mark Goulthorpe), the elevation of automaticity in construction over the intelligences of the hand and the eye? How do latent class concerns play out here?

What in my own method is most similar to the tendencies of contemporary computation? Perhaps a methodological approach that proposes that mistakes – variations from normative logic sets – provide the opportunity for a new design intervention?

How may one embed this intuitive problem-solving back into the design process? Can this occur by problematizing errors – which exist already in the context of craftsmanship – within a different paradigm for resolution?

---

Thesis Review II
February 25, 2010

Gathering drawing tools…
February 14, 2010

In masonry, what are the tools for drawing in space?

The chain, string, plumb, line level, straight level, template, compass and rule, angle and tape, cintrel…

All serve their purposes in the registration of the masonry system.

These spatial drawing tools will be considered throughout the design process, constituting a 4D masonry drawing projected on the plane of design representation.

---
Thesis Review
February 10, 2010

An account of my first thesis argument follows: "The 4-Dimensional Masonry Construction", explicitly a design-research thesis in the area of structural masonry innovation, proposes that considerations of the 4th dimension – the extension of design from a spatial to a spatio-temporal paradigm – critically engages contemporary disciplinary divides between design, material science, structural engineering, and construction.

#1 – 4D STRUCTURE. The thesis will take as its benchmark a radical efficiency, 'economy of form' and perhaps contradictory aesthetic extravagance in structural masonry innovation, as developed through the works of such engineer/architects as Rafael Guastavino, Felix Candela, Eladio Dieste, and Antoni Gaudi. Such design may be considered as 4-dimensional in the responsiveness of structure and form.

Additionally, three important areas of technical and aesthetic innovation – linked together through design-research investigations – will culminate in the construction of several medium-scale studies and the design and construction of a full-scale vault prototype:

#2 – 4D MATERIAL. A radical economy and reconstitution of material, which will seek to tap the consumer waste stream, invert resource flows and invent carbon-sinking masonry structures. This material innovation takes as core principles the ideas that material properties dramatically impact structural behavior (thus the aesthetics of new forms), and that broader, time-scale considerations of material impact environmental ideologies in the discipline.

#3 – 4D TECTONICS. Analysis and invention in the area of
systems aggregation, which will investigate limit-stages in the relationship between masonry unit and system, intersections and aggravations of structural, pattern and constructible geometries in brick. Such limit-stages will engage aesthetic, material, structural, and tectonic constraints – and translate between design, material science, engineering, and construction – to produce new forms. Such limit-stages engage both technical and aesthetic themes of architectural eschatology, critical also, as mentioned, within contemporary trends towards considerations of life-cycle sustainability. Further, the interrogation of the masonry unit problematizes the terrain of industrial productivity in brick manufacturing, and will seek to develop systems of structural and tectonic idiosyncrasy through variation of the brick unit.

#4 – 4D DRAWING. New conventions and aesthetics in architectural design drawing – the 4th dimensional drawing. This is, quite technically, an impossible construction, a representation of the 4th dimension in a plane projection. Such a temporal masonry design drawing calls forth paradigms of translational design and construction craftsmanship, as have been articulated through the historical, cultural, and geometric scholarship of Robin Evans on stone stereometry and Gulru Necipoglu on Islamic geometric construction. The end-goal of the 4D drawing is the conflation of design and construction autonomy – the consideration of the design drawing as a pseudo-spatial act of construction through the operational tools of design, and the consideration of the masonry construction itself as a ‘drawing in space’ enabled through the operational tools of the hand and the eye.

Taken together, these innovations of the 4th dimension are intended to synthetically drive design logics which are both architectural and constructional, technical and aesthetic, technological and craft-based. Design of the 4th dimension is a mode by which the act of design and the act of construction are reconciled through an interpenetration of the logics of each. Here, the skill-sets of the builder and those of the architect are exchanged.

Late night folding of the mind…
February 10, 2010

There are moments in one’s life that are something like the paper folding metaphor of Teilhard de Chardin… biology itself complexified with a continual folding in and over of things previously folded. Recursion and re-clarification of old intuitions.

Yesterday, I found a slip of paper from before 2005 with a rough sketch of a tangent array, some natural cut stone piecing, and a cryptic speculation of the work I would have done – I wanted to do – had I known how:

1/2 Geometry
1/2 material science
+ 1/2 intuitive puzzle-making
I suppose that just about adds up to my thesis: 1 1/2. A veritable 4-dimensional ‘becoming two,’ with all of these parameters as critical facets of the work. What I mostly could not articulate at the time, was how to make geometry structural and not simply pattern making. I can say now that I have a very good grasp on this topic, and that I will attempt to reconcile structural geometries and pattern geometries through this study. If I can do it – as I can now actually imagine – it will most certainly be the thing that I came to MIT blindly grappling for. Funny how life folds back on itself when one searches for the threads which haunt us. Even masonry itself can be made to fold – the very best of Rorschachs for one, Lara Davis.

Self-reminder to talk to Erik and Marti Demaine on this one.

---

4th dimension – a diagram of space-time
February 8, 2010

Tags: 4-dimensionality, Craftsmanship, Projective Geometry

After some long discussion last night with Mallory on such various 4-dimensional themes as Maxwell’s equations of electromagnetism and Charles Hinton’s hypercubes, it has occurred to me (further, really) that the 4-dimensional drawing is an impossible construction, that such a drawing may only be the image of a spatio-temporal phenomena represented (or diagramed) in plane projection. The real 4-dimensional drawing is the time-based act of construction. The construction of masonry itself may be mapped out as a 4-dimensional drawing, but more importantly, the 4-dimensional drawing is constituted by the establishment of the registration for masonry construction. The line, the line-level, the level, the plumb, the angle, the square, the template, the trait… the eye, most importantly; these are the tools of registration which set the unbuilt masonry construction into a spatial framework, which translate it from a 2-dimensional drawing into a 3-dimensional space, by way of an operation of the 4th dimension.

Does this 4th dimension exist then? Only insofar as it expresses a series of points in time which describe the unfolding of a construction. But if we were to take this 4th dimension into the representational space of the design drawing, what would it look like??

Thanks, Mal… the 4th dimension only exists if perchance it is registered by the eyes of another, even if just the tracing blip on the screen in the broader context of the mysterious formulation of design.

---

The Masonry Design-Research Laboratory :: Heros of Method
February 7, 2010
The methodology for the design and production of this thesis falls into the context of the “Design-Research Laboratory”. Departing somewhat from the typical constraints of a holistic architectural proposal (site, context, program, discrete building), what I will investigate through this Masonry Design-Research Lab is a complex of material, structural, tectonic, constructional, and aesthetic criteria. Each productive investigation should in fact be testing multiple criteria at once – for instance in structural cantilever and aesthetic form.

Such is the nature of the very history of the ‘design-research lab’: multi-criteria oriented. Many of the pedagogical forefathers of this approach have been taken up in the discipline of architecture, including the tremendous influences of Laszlo Moholy-Nagy and Gyorgy Kepes at MIT. Perceived as a dilittantish approach in contemporary academia on account of the vast specialization in the discipline, such an intensive multiple-criteria investigation has gained as a value proposition for the integration of disciplinary facets and serves to question the perennial optical dominance in design method. Moholy-Nagy’s “Sense Labs” of the Bauhaus and New Bauhaus periods enabled a critical role for sensory perception in design, while juxtaposing such ‘immeasurable’ qualities always within quantitative analysis. Moholy-Nagy – the vestigial father of late modernist architectural education – will be an unsung hero in a methodological approach, which is neither wholly technological nor emotive/intuitive, neither wholly invested in engineering nor aesthetics. But a translator of each to the other.

One other unsung methodological hero is Robin Evans, the tremendous historian and theorist who passed away far too early nearly 2 decades ago now. We still miss historians such as Evans, increasingly so today. Evans’ profound investigation of stone stereotomy (in The Projective Cast) is a great model for the way in which technological constructions impact social histories and social constructions. As it is a goal for this project to bridge design and construction through the 4-dimensional drawing – a spatial, constructional drawing of masonry – Evans’ discoveries about the higher geometric operational nature of stereotomy will be critical in formulating the underlying principles of the thesis. Evans writes:

“Stereotomy was at the very edge of architecture. Is was also at the edge of mathematical geometry, at the edge of technical drawing, of structural theory, practical masonry, and military engineering.”

The avant-garde sets itself apart, a military advance in concept, a leadership but nevertheless a defection from the body. But methods such as stereotomy were at the edge, not the fore. And so, too, will be the design-research laboratory for the 4-Dimensional Masonry Construction.

Material studies lab
February 7, 2010

Contemporary design education eschews material studies – material is itself treated as no more than a surface aspect of a protean or chameleonic design form, which may be ‘rendered’ with any other appearance. As long as we treat material as an optical effect rather than as a multi-sensory
and structurally, environmentally, and spatially performative medium, we are designing with only half of our capacities.

Perfection – or design?
February 5, 2010

Tags: Craftsmanship, Logics of design, Transgressive patterning

The greatest tools – it may be argued – that may come into the domain of the artist, the designer, the architect are actually mistakes of the n-th order. Mistakes, or anomalies really, which depart from normative methods, yet which still cling to convention in such a manner that they may still be evaluated for their functional or aesthetic use-value. It is beholden to the designer to notice these anomalies as they occur in the process of design, for when one tacks into their direction, innovation occurs.

And so, the very concerns of masonry idiosyncrasy which have been only just barely touched upon below (see “The Beginning”) give us pause for two possible paradigm manifestations of detail in design and construction: The one, is the perfecting of craftsmanship sought by both our design and construction sectors, in their own ways of course. The other, however, is the harnessing of the mistake – the elevation of the anomaly – towards the goal of innovation.

Now, if one may lay the perfect course of bricks as it is described by the design drawing – keeping the proper registration line, angular orientation, mortar course width and surface aspect – we say that this is a success of the craft of construction. It will come to describe, in a system of such bricks, the perfect surface. Conversely, it may come to pass that the bricks are imperfect and, for instance, crooked ever so slightly to one side like a banana, and the builder notices a moment at which the perfect coursing has taken leave towards the establishment of a new imminent pattern. Where the receiving brick edge may call for ‘banana left’ to keep proper the lines of coursing, its chiral opposite has been used, which will break the line and create a cascading system of courses which tend towards the right. The builder has the options available to correct this imperfection, or to exaggerate it. Where the former would also be called a success of the craft of construction, the latter may be called a success of crafting through design, which consciously departs from normative patterning in pursuit of a new aesthetic.

The purpose of this thesis is to identify imminent patterning anomalies which may occur in typical constructions, to wield them intrinsically towards the goal of their aggregative transgression, and to establish such transgressions of pattern as aesthetic potential of contemporary masonry design.

Why, it might be asked, would contemporary masonry design tend towards the transgression of pattern? Keep posted, dear reader. Such is the mischief of design.
The Incommensurate Logics of Designing and Building?
February 5, 2010

I have discovered over the course of my design education that there are many instances of contemporary design technology that simply cannot translate into constructional logics. This is perhaps difficult to qualify... but take the Rhino model, for instance: it is theoretically perfect in its geometrical tolerances. So we think, and take for granted in any case. The operative tools of a digital space create their own illogical geometries—interpenetrating volumes, visually convincing connections which cannot be made to intersect. But, in masonry, it is their perfections that are most hazardous—as the previous post has suggested.

There is a certain point at which the Rhino model ceases to be the accurate rule for measurements in the field... and where another logic must intervene somehow. Perhaps this is at once too esoteric and also too simple. Perhaps this is the preemptory declaration of my defection from design. Ah, but I don’t think so. I believe that there are intuitive design—not merely construction—logics which cannot be made to comfortably exist in sections, plans, or 3d digital models. They constitute a sensory mode of adaptation, where the imperfections in the translation from paper to material call for design interventions of the hand. The optically-biased design logic is supplanted by the hand-based design logic, since these sensory cues develop into an analytical puzzle. I may look at a vault, for instance, see it standing, and think that it is perfectly sound. But to tap that same vault—to feel the inflection and to listen to the acoustical feedback of stable and unstable regions—engages a sensory cognition which may be relayed back into a design process. The graphic tools of drawing and presentation may be the first and most dominant language in architectural design, but they are not the only language.

This thesis will seek out these interstitial, translational linguistics... the intuitive kauderwelsh between the dominant logics of design and those of construction. It will interrogate the technologies employed, their applicability to both sets of logics, and their weaknesses in translation. And it will look to historically precedent masonry technologies and techniques to provide a model for both theory and praxis.

The beginning. From 3d to 4d, the trick is how one starts
February 2, 2010

A repeat-post from ‘vaulting’...

The consolidation of four-dimensional design:

Consider for a moment that a masonry structure is composed of details, many details, which in their whole organization must come to work as a system. So now, when we look at the detail—our brick—we must always see two things at once: a unit (which has its ideal position) and a system (composed of these units). In a 3d model, these units always fall in their proper place—but a brick, well, it is an idiosyncratic thing!
Each brick has its own shrinkage proportions based on its position in the kiln and exposure to heat, it has cracks which distort it, it has uneven edges on the surface side of sand-molded bricks, such as the ones we are currently using. Each brick has a different water content (since they must be soaked in sequence in preparation for laying). Each brick is laid in a sequence of plaster mortar batches, during which period plaster changes its character from wet and runny to dry and thick, thus slightly altering the thickness of a mortar joint. These are some of the many myriad of things which make a brick an idiosyncratic detail of a highly organized system. So the devil is here in the details... in sorting them out to best position a wonky brick (this is a technical term), and to see the whole system in such a light that it may respond to the alterations that each brick induces into the often cascading distortions of a system. But to see these dramatic distortions, one must anticipate them as they aggregate, indeed, one must anticipate them in the very inclination of each brick. And the difficulty of this task increases as the geometry of the overall system is complexified.

For this reason, most especially for complicated geometries, registration or guide lines become very important to ensure that the masonry system does not distort beyond an acceptable range. In our case, with a one inch thick shell, the most critical distortion which cannot be accepted is that which falls significantly outside of the range of our catenary thrust lines.

For any pattern that is established as a masonry system, there are counter-patterns which the bricks may take. Personally, I find these patterns extremely interesting, so I study them. They are often as beautiful as a regular masonry pattern, yet they have a tendency towards entropy - a pattern that destroys itself. The mason directs negative entropy in the system, the entropy which must be exported for the system to correct itself.

---

Backwards: From Construction to Design
February 2, 2010

Tags: Design vs Construction, Systems analysis
4-Dimensional Masonry Design will call into question the hierarchies of method in contemporary architectural design. Where a typical design methodology might evolve from aesthetic studies, into systems analysis, further to engineering considerations, and then finally into concerns of constructibility, this thesis will invert the temporal hierarchy of design and propose an interrogation of time-based methods in construction which inform the design process.

By working backwards, so to speak, construction and engineering will be positioned as integral aspects of masonry design, and design itself will be inflected with the aesthetics of constructibility. What does this mean, you ask? What does it mean for a builder to design, or for a designer to build? The history of masonry innovation is rife with these questions, and the tools of the mason will be studied here for an inversion of traditional craft into a query of new aesthetics in contemporary masonry design.
BLOG DISCOURSE:
MIT MASONRY RESEARCH GROUP
A 16 foot span, 1-1/2 inches thick, 720 bricks throughout the vault surface – all within a construction schedule of FIVE days. Was it possible, we asked? Yes, conceivably. Did it leave any room for error, however? – Not a stitch! These time constraints – from the beginning – were the driving factors in the vault design which emerged for the Cooper-Hewitt: a creative, innovative outcome for the desired geometric complexity, which could still be buildable within this very limited time-frame.

However, all design must anticipate material and human error, and confront inevitable problem-solving on site. As was the case with our construction – which could certainly not afford such delays. So, after a rather gross formwork tolerance error – which cost us one whole day! of delay – the race was really on!

The result was one of the tightest deadlines and most fast-paced constructions I have ever participated in. In three days, with two bricking teams and four other crew members on various critical support tasks, we finished the vault! I am reminded of the old adage, “Haste makes waste!” However, in our case, we already had waste... 4 whole palettes of it, formed into beautiful bricks. Our break-neck speed certainly required certain moments of clear reflection, as we observed small errors and the manner in which they needed to be corrected. At all moments, we had to be critically attentive of such small errors to insure that they did not cascade into problems which could not be corrected – either deviations from our structural catenary geometry or deviations from the pattern system of the masonry. Under the constraints of this time, it is very satisfying to look up at this vault, to remember our hands as they placed bricks, to celebrate the idiosyncrasies in the position of each masonry unit, and to praise our stars that there are bricks overhead!
Props to the Installation Crew
APRIL 9, 2010
by limacon24

So, I should stop stalling and get to it – the construction at the Cooper-Hewitt! Before describing our insane 5-day trials, however, I would like to thank our installation team. For a number of reasons, we had to call on some somewhat less experienced hands for this construction. However, I really believe in the end that it was most possible because of the impressive skill, patience, persistence and hard work of our crew. The generosity of this group, who volunteered their time and gave up their spring breaks to build this project, was deeply impressive to me. Invisible laborers always get very high marks in my book, and I am truly grateful for the support we had – within our team and at the museum.

Our particular gratitude goes our to Matt O’Connor, the production manager of the Cooper-Hewitt, and his extraordinary team, foremost, Kevin, Jim and Roy. Their material support – and their great humor – throughout this construction made it not only possible to complete, but really a great pleasure to build.
The Adaptation of the Unit
APRIL 8, 2010

by limacon24

Nevertheless, one very marked difference between the prototype brick and the Cooper-Hewitt brick spelled for us an imminent constructional problem – GL bricks are 1 - 1/2" – 2x thicker than the bricks used for the January prototype, increasing the structural safety factor of the vault, but also very much increasing the difficulty of setting them into a doubly-curved surface with very tight tolerances for the turning radius of each brick.

Thus, in order to build this vault at the Cooper-Hewitt with Green Leaf bricks, a very strategic constructional logic had to be employed: Rather than the somewhat predictable but also relatively arbitrary custom-cutting method employed in the January vault, the custom-cutting for the Cooper-Hewitt vault had to be highly specific to the vault geometry and planned well so that we could still keep our (very tight!) 5 day construction schedule. It should be noted here that one of the most formative constraints for the design of this vault was that of time. The curvature of the vault is composed of splines which vary in profile but are fixed in length – all in order to keep an equal coursing pattern and to save in the time and labor-intensive process of custom-cutting bricks.

What I planned was the following: Each custom-cut brick would have the quality of one of three different brick modules, a primitive which could be chirally oriented for a left or a right, and combined with other primitives as necessary. A logic for the quantities required for each custom primitive was also very important, so there were always enough of the critically necessary variations as we began to brick the sections which required them. The results were very successful – Sam Kronick was our dedicated brick cutter, who spent a good deal of the construction cutting in the basement with the wet-saw and delivering our variants for their rough schedule in construction.

This is an example of what I would call constructional logics that are 1) learned from building (in this case, in January), 2) analyzed and abstracted as rules, and then 3) re-embedded into the design process. It could be said that this is merely the practice of good craft in building, but I would argue also that – by fundamentally altering the logic of the brick unit, from a regular and industrially produced module, to a taxonomic system of limited, customized module variations – the design of the brick is a creative proposition for challenging constructional constraints. Now – while this vault could not have been constructed with standard brick units, the project of my design thesis is to show what non-standardized
and variable units can - as a system - be made to build. The altered brick unit, the system of aggregated units, and the method of assembly would in this case come to reciprocally generate each other.

Green Leaf bricks – 30% [****]
APRIL 8, 2010

by limacon24

From the prototype vault built at MIT in January to the exhibition vault built at the Cooper-Hewitt, the most significant difference is the brick itself. Our tremendous gratitude goes out to James Kolodziey and Charles Taylor at Green Leaf Brick and Taylor Clay Products; they have been instrumental in stepping up the manufacture of this highly custom-produced material to meet our construction deadline. I have learned a great deal about the efficiency of manufacture in the industry, by coming to understand what it takes for a brick plant to clean the lines of production of a mass produced brick in order to push through a small production run. It must be akin to heard-farming really, for a plant manager to get as many of one type into a sequence as possible, to keep the ‘down-time’ of cleaning and set-up between manufacturing runs from eating the costs of production. Our team at Green Leaf and Taylor have taken considerable pains in the name of productivity for this vault to be built, and we hope very much that this will pay forward for them in some way.

Green Leaf brick is a 100% post-consumer and post-industrial recycled material composed of:

30% processed sewage waste
by-products of open pit-mining operations
recycled glass
virgin ceramic scrap slated for landfill
industrial dust filtration contents among other things...
The clay engineering of these bricks is extraordinary, and its engineer, Steve Blankenbeker, has demonstrated that this brick is part of a long tradition in scientific innovation of conventional, industrially produced brick and experimental sustainable production methods. Through Steve, I have come to know the incredible culture of brick production, which ultimately crosses over into the terrain of geology and material science.

It has been a great pleasure to work with these bricks – and I do not intend to be hyperbolic here. The perfect regularity of GL bricks make them very predictable in terms of how they behave in the vault construction – and perhaps contradicts one's preconceptions of so called recycled products. Their heft – well, this somewhat underscores their being composed of 30% shit! I assure you, we have had many-a-person inquisitively smell them – but one is hardly likely to get a whiff of anything after being fired above 1,900 degrees!

Catching up...
APRIL 8, 2010
by limacon24

We hope that the readers will forgive this small time delay... It has been a rather challenging task for our team leadership to take on the final phases of design drawing, structural engineering calculation, materials testing, installation crew organization and training, Cooper-Hewitt museum communications, project budget management, final fabrication, materials preparation and delivery, tools assembly, and construction management. It has been A LOT of work, but nevertheless an extraordinary experience for design students to negotiate these diverse terrains from design through construction – with the accountability required for construction in a historic museum such as the Cooper-Hewitt.

With this disclaimer, in the following posts, I'd like to catch you up on the events of the last week. Eight months of preparation – material and constructional prototype testing, design and engineering iterations, specifications and construction sequence writing, communication with manufacturers, exhibition coordinators, production managers, engineers of record – have made this construction possible.
Scaffolding for construction
MARCH 4, 2010

by limacon24

And so here we are... in the home stretch to brick at the Cooper-Hewitt, beginning March 22. This is when the most planning must come to be implemented, when the greatest number of translations, delegations, and details must be accomplished to manifest the extended, collective cognition of our team. The scaffolding of the minds must support the complex organization of the building project, just as the centering must support the incomplete brick vault. This - in my mind - is the most glorious part of architecture, sadly missing from academia: Teamwork. Coordination. Delivery.

Stay tuned... The production has been designed, and the C-H show is about to begin.

Construction time-lapse
JANUARY 28, 2010

by limacon24

The final construction time lapses have been assembled. Short but sweet. We hope it goes so quickly for our 5 day construction schedule at the Cooper-Hewitt!

Demolition – the long version
JANUARY 27, 2010
Especially for the die-hard structural engineers, here is Part I of the demolition: the 10 minutes of springing displacement and intermediary failure before the final collapse (Part II in previous post). It still has its dramatic moments and demonstrates the hinging mechanisms which form in the vault, leading to its collapse at 6 inches of displacement. Keep in mind that there were also several significant sledgehammer blows directed from the inside of the vault around the quarter-span region – precisely at the level where we will see the final failure hinges.

End-Game: Vault Demo

JANUARY 24, 2010

Play as we did, the real end-game – as JAO mentioned – was the inevitable dominance of gravity as Silman gamingly abused our vault. The final event – to destruction – would test our design intention to accommodate all horizontal thrust through friction along the base of the vault springings. The Silman engineers marked out half-inch increments and then displaced one springing with sledgehammers to see how long it would hold up, observing at each major behavioral alteration the cracks and mechanisms which were developing in the vault shell.

“So it is down to you, and it is down to me! If you wish her dead, by all means, keep moving forward.” – TPB

But since she did hold up rather long indeed – for an awesome horizontal displacement of approximately 6 inches, “off the charts” – I will include now the sudden-death moment of demolition, and add the drawn-out version for the structural masonry fanatics when I have 4 or more hours of uninterrupted upload time...

What remained was intriguing, really. That undulating vault is no more; but – even in ruins – she still had her curves. Our great thanks to the engineers from Silman, Smithsonian reporter Logan Ward, MIT wood-shop director Chris Dewart, JAO, and the vault team!
And so it has come to a close. The end-game for this January's prototype vault was a project for the Masonry Research Group and Robert Silman Associates, the structural engineering firm charged with the verification of our vault's structural stability and safety. The task was to de-center the vault under their observation, and then to test the many ways in which it might be made to fail. A coup for the Masonry Research Group would be a successful de-centering – and then the longest endurance against the beatings of our counterparts in construction: Silman the demolishers!

But what playful and sensitive demolishers they were. Have you ever heard of a destroyer who listened with his hands? During the second video, Derek Trelstad sounds the frequencies induced by the hammer with his hands, measuring the differential between those frequencies conveyed through the end arch of the vault and those conveyed through a section that he had smashed-in with a rubber mallet. More such tests occurred... indeed, our vault became the structural jungle-gym for our engineers as they sought out the weaknesses and strengths of our vault – our advisor John O among them of course. It was really quite amazing to watch them all in action. Despite our team's initial reluctance to destroy our first undulating, unobstructed view of the de-centered vault, we soon caught their spirit and followed suit:
De-Centering
JANUARY 24, 2010

by limacon24

De-centering was a little hair-raising, especially with an audience, but watch her fly!

![Image of construction site with workers and equipment]

![Image of curved structure with covering material]

![Image of close-up of construction details]

![Image of another angle of construction site]

![Image of another close-up of construction details]
The Closing-In
JANUARY 24, 2010
by limacon24

We haven't posted in a few days, an effect no doubt of the crunchy lack of sensation in one's fingertips and the moderately enfeebling effect of daily overexertion – perhaps from carrying the extra weight of mortar in cuffs, pockets, and hair, to be later deposited on the floor of one's apartment. So it feels as though I must go back to briefly recap the closing. Indeed, very briefly.

In fact it was done almost as soon as it had begun; in six days, all masonry had been laid. The most challenging – and yet gratifying – part was the closing-in, each course in succession as its last bricks were laid to complete an arch. These sections had constructional complexity that involved: 1. custom-cutting of bricks to fit within the arches, 2. a condition of full cantilever in which, against gravity, the mason must support bricks until mortar has been sufficiently set, and 3. the most extreme curvature of the vault which required steep joint hinging and difficult mortaring between each course for it to turn into the curvature.

Though I might add that the greatest difficulty by far was squeezing into or over the deep and narrow grid-shell compartments of our formwork. Since the brick itself was designed by the measure of the body, I think we will probably reconsider the usefulness of such simple measures as shoulder-spans in the next version.

Through these days, my greatest thanks go to Mallory, my mortar mixing and brick-laying teammate, who worked patiently alongside me to spot me in the hairiest of moments, to read, anticipate and direct the myriad of tasks necessary to set a good brick – and occasionally, to catch a falling glob of wet mortar. None of this work would be possible without the patience, timing
and teamwork between the members of our vault crew – in all facets of vault design, formwork design, materials sourcing, fabrication and construction.

The satisfaction of the final brick was meant to go to John O's toddler, whose timbrel-flavored, multi-syllabic vocabulary includes such words as "Guastavino" and "Barcelona". We considered how perfect it would be for John to claim to his future students that his daughter completed her first vault before age two. Not this time, I'm afraid – though she did practice with warmish globs of play-doh Hydrocal, holding it up with a brick as though to indicate she knew they went together. Soon enough, young vaulter.

---

**Seeing a Surface**

**JANUARY 17, 2010**

by limacon24

I will take up Scott's last thread, in the hopes to spur a blog-debate to keep our minds active while we work:

It is true, new technologies such as CNC fabrication do enable new aesthetic and structural potentials, which were unavailable to previous architects, engineers, and builders of masonry. However, I believe – more importantly perhaps – new technologies also create new kinds of errors, which require innovative responses. And it is the process of discovering error through models and full prototypes, as this one, which allows a design to evolve. What I find extremely applicable here about the greatest structures in the history of masonry innovation, is that their daring created problems which had to be resolved by their own architects and their inheritors. Just as di Cambio constructed the 42ft span octagonal drum for the dome of the Florence Cathedral, which could not be built for more than one hundred years, until Brunelleschi's double-shell innovation proposed to span it without formwork. Just as Isodore of Miletus and Anthemius of Tralles built a dome which collapsed repeatedly, and had to be repaired and renovated by Sinan and other Ottoman architects. Just as the fear of collapse of the dome of St. Peter's caused Poleni to so greatly advance contemporary theory of masonry structure through his analysis of Hooke's 'hanging chain'. My colleague Peter Christiansen once queried whether it was the history of innovation in engineering which led to such impressive structures, or whether it was the failure of impressive and daring structures, which required – post-hoc – more significant advances in structural engineering to solve the impossible problems they first presented.
I do not believe that we can stand upon the shoulders of the masonry greats, simply because they have been built and engineering has advanced – because we have not yet had the opportunity to learn first-hand from their failures. Perhaps we will. Several weeks ago, some generous project managers of the MIT dome renovation took me for a tour: The view from the very top of the dome is one to which only an MIT hacker so aspires, ah, but more exciting by far was to see what Walsh Brothers excavated from the experimental original thin-shell dome skylight, which has been leaking since before WWII. And so much more by far, the view from between the two domes: the indexes of ship-building technology in formwork board marks on the inside of the outer structural concrete shell, arrayed willy-nilly with no apparent geometrical coherency – yet still describing a perfect surface for the eye of these early 20th century masons. How does the mason see this surface? How does the computer see it?

This grid-shell of formwork profiles and thin grid of mason's line approximates a surface, which our team must now begin to 'see' with brick. It will not be an easy task to develop the skills of the eye in 'lofting' such a surface, though these are skills to which the human eye (and in particular the eye of the mason) is much better adapted than the automated robot – as Gramazio and Kohler of the ETH in Switzerland have discovered through their robotic masonry constructions. This surface curves in two directions, and each brick must be placed with respect to its relationship to its neighbors and its role in correcting, adjusting, "splitting the difference" in the errors of its neighbors in describing the whole surface. This is the fun part.
Risk ≈ Gain  
SEPTEMBER 12, 2009

by limacon24

For those who were not present at the opening – and unable to witness our extravagant performance – I will describe for you some of the events that transpired last evening:

With a few small miracles in finishing some difficult sections of the vault and some very rapid, large-batch mortar rounds, we managed to complete the construction of the primary section of the vault in time for the exhibition opening. Our vault was completed with a small oculus at the pinnacle of the dome, both as a testament to its thin-ness and to our tight time-table, as well as a gorgeous teaser of interiority for a vault lit from within in the late evening. I myself had no time to shift identity from construction worker to architect, and so attended the opening clad head-to-toe in wet clay and plaster, passing somewhat precariously through crowds of tidy, black-clad young architects. I always love this moment, when roles may be reversed and the unspoken (perhaps latent) class divisions between the design and the building culture are subtly undermined – except normally I like to be the construction worker who morphs to architect/ intellectual in slightly more classy attire.

The risks that we have taken in the construction of this vault, in our eyes, have been absolutely proportional to the gains in our design and construction education. The task of translating into construction design (and the actual building itself) of Philippe Block’s complex curvature, as well as the task of building with a very low carbon footprint – all in an extremely short time period – are numerous and self-evident: 1. The choice of an unfired brick (never really meant to be used for such purposes), which resulted in both risk of water damage and the difficulty in adhesion of masonry to mortar, 2. the decision to build at our full scale of 21’ x 15’ x 10’ high, 3. the unresolved design issue of how to best approximate such complex curvature for the brick-layers and avoid local regions of negative curvature, 4. the very real significance of building such a complex structure with student architects (and not more experienced construction workers or masons trained in the eye and hand techniques of thin-shell vault construction), and 5. the timing of the project, which beset us with the task of resolving our material learning-curves even as we built the full-scale structure.

And so – there it was at the opening, finished. Would it stand or fail? Which variables of risk might govern our failure mode, if it were to occur? We decided that the wagers taken to realize this vault only begged for the greatest gamble: to de-center the structure with a full audience. We had removed one centering carefully before the exhibition, and – with the un-impeded view of the underside of one perimeter arch and the curvature of our vault springing – we gained confidence that our public de-centering would indeed demonstrate vaulted splendor. Our greatest error was that the time, and the pressure of public viewing, did not allow us to more carefully coordinate as a team in the de-centering process. Rather than de-center slowly and carefully the way the centering had been designed for removal, we opted for the more rapid and perhaps ‘ta-da’ method of the whole form removal – again, with much greater chance. During the removal of the formwork for the large end arch, the masonite surface (upon which the brick arch was bearing) was pinched by the OSB panels of the main formwork, pulling on part of the arch which had bonded to it. The result was a local failure of that eyebrow arch, followed by a crack along the opposite side of one groin, and
then, perhaps 4 seconds later, by the collapse of that springing and the whole vault with it. Despite all of the risks involved – it was nevertheless a shocking occurrence for us.

My dear friend Mary Fillman, who graduated from MIT Department of Architecture in 1956, came to the opening and reminded me of the long history and celebration of such prototype risk at MIT. She said that Bucky Fuller would have loved this test (and the failure of the vault), and talked about Félix Candela’s frank conceit that he had learned the art of building such complex hyperbolic paraboloid shells through the collapse of several early prototypes. As you will remember, it is David Billington’s exhibition of Candela’s work that inspired the first proposal for our group’s MIT Museum grant submission, and John Ochsendorf, our advisor, who was a student of Billington. Such precedent cases of risk and collapse are irrevocably linked to innovation in the field of structural masonry. Indeed, the flavor of the exhibition itself seemed in some way to celebrate this history of innovation risk at MIT and our own part in the development of experimental thin-shell masonry structures. The time-lapse sequence of our vault’s construction, projected on the wall in the museum, animated the shattered shell in the courtyard with a sense that we pushed the limits of what we knew to be possible in both our design and construction capacity. And though the spectacular failure of our vault has been somewhat disappointing for us (and even perhaps, for a moment at least, just a hair demoralizing in such a public context), well, frankly... it’s pretty cool to watch a vault come down!

Risk and gain are bound together in innovation, however, only when a commitment to further innovation is present. This entire process has offered us a profound learning experience in which our design, material research, structural analysis and construction techniques have been tested. This vault has taught our team tremendously – even more so through its collapse. And I will speak for myself here, in saying – I look forward to implementing these discoveries in the next vault.
MATERIALS RESEARCH:
THE ELUSIVE GREEN THIN-BRICK:

"Is your green brick at the end of the rainbow, Lucky?"

What follows are my findings in the first phase of thin-brick material research and sourcing. I spoke to a contact of mine at the distribution company Consolidated Brick, Lynn Donohue, and she started me off in the right direction and assisted in compiling a short list of thin-brick manufacturers and plants. By going directly through the manufacturers, we could better identify the qualities which make a brick 'green' or 'not green'; and doubly increase our chances of a donation offer. My best neutral resources for the following information have also been Mike Longo (at Marion Ceramics, SC) and Gregg Borchelt (BIA, Brick Industry Association).
First, of the thin-brick manufacturers, most will say upfront that they don't produce sustainable or green thin-bricks (including the Belden Brick Co., Redland Brick Inc., etc.). Many manufacturers are using reduced-carbon techniques for full-bed bricks, but not for thin-bricks. Important Note: The catch phrase 'sustainable' may mean many things for brick, which I will attempt to outline in detail below. To simplify, however, a low-carbon footprint for brick may be achieved most commonly by a low energy-intensive or reduced emissions firing, reduced energy in transportation, or recycled additives in the clay admixture.

To start, thin-bricks – by nature – are already low-energy intensive bricks for the following reasons: 1. The clay masses in the firing are much smaller, so much less fuel is required to fire the clay all the way through to a proper bisque – ranging from a 20% to a 70% fuel reduction depending on the manufacturer and plant. NOTE: This advantage is made null by manufacturers that fire full-bed bricks and then face-cut them into thin-bricks. 2. The number of bricks in the kiln is greater – more output per fire. 3. The transportation of thin-bricks saves purportedly on fuel on account of the light-weight nature of the thin-brick (ie. ~17% fuel reduction). 4. The total sq. footage for on-site use (depending on construction technique) is generally greater.

That said, there are some companies that purport to produce 'sustainable bricks' with a cagey logic. To clarify, ALL brick is made with grog (~15%), ground up material in the clay body which makes the brick more porous, allows for the release of moisture during firing, and enables an even bisque fire. Most grog, however, is pre-consumer – not recycled material, and it is quite often regular, high-quality fired brick simply ground up afterwards. So when manufacturers claim that their thin-brick is green, because they use grog, it's phooey nonsense.

According to the engineer, Gregg Borchelt, at the Brick Industry Association (and a few other resources), the techniques below may be used to make a 'green brick'. Unfortunately, to Gregg's knowledge, none of the plants that are using such techniques are also making thin-bricks – I have followed up on this with quite a few manufactures and tend to agree with him (Boral, Marion, Endicott, etc). For this reason, I have come to the conclusion – though I still will look at some calcs – that for thin-bricks, some of the most significant energy reductions involve the fuel source for firing, on-site manufacture (a reduced distance from the point of extraction to the point of manufacture), as well as local plant use (reduced distance from the point of manufacture to the location of final use, MIT).

"Green Brick" techniques:

1. In terms of industrial re-use, gravel mining involves a stage in which the fine particles (sands, soils) are washed from the gravel. These fines may be reused to supplement the brick clay body.
2. Hardwood sawdust may be added. This burns out during firing, leaving a lightweight brick that consumes less energy in firing and transportation, while using waste sawdust from mills.
3. Similarly, tailings from mining operations may be used – though, I have now learned from James Kolodziey that his tests have shown that fly ash in fired clay bricks makes unacceptably brittle bricks, whereas high performance industrial starches are very effective for good clay bodies.
4. Brick manufacturers may also use culled bricks (broken/ deformed/ etc. reject bricks) to regrind into new clay bodies. (Aside: I have read elsewhere that this material may in certain circumstances have a pozzolana effect for mortar reuse, but I haven't verified this.)
5. Manufactures may be even more frugal and use other miscellaneous recycled ceramic items such as ceramic bathtubs (ie. Green Leaf Brick, SC).

6. Coal or natural gas is mostly used to fire brick. The most significant contribution to the illusive sustainable brick may very well be those manufacturers, that fire their kilns with methane from waste control facilities (ie. Boral, Terre Haute, IN – landfill gas and mining overburden). This is a more carbon neutral and ‘free’ energy resource the EPA considers to be renewable, though it is rare on account of the upfront costs of piping for such a manufacturing plant.

Note for future: The BIA is working now on a 3rd party certification program in conjunction with The National Brick Resource Center at Clemson University, in prelim stages but to be written up soon in Architectural Record. This would enable users to seek out (and rely upon) the material and process specifications that different manufacturers (and individual plants from each manufacturer) are using in their brick production. There are arguments, however, that an $8000 upfront cost, significant annual fees, and total transparency of unpatented clay technology is not very good for small businesses.

Other notes and assumptions: Most thin-bricks are meant for use as veneer (aka ‘veneerial disease,’ according to Santiago Huerta), and thin-bricks are not the same as structural clay tiles. There are only a few thin-brick types that distributors will vouch for in terms of strength, longevity and weather resistance, particularly in freeze-thaw climates such as Boston: ASTM C-1088 thin-brick, grade exterior (ie. the Tru-Brix system). I have assumed, however, since I believe that the MIT vault will be standing for a relatively short period and the Cooper Hewitt vault is indoors, that a standard thin-brick is more than acceptable. John, please verify.

Present Options:

1. Gary Davis at Endicott Clay Products Inc. in Nebraska has provisionally offered us a donation of our requested brick amount (preliminary spec at <1000 bricks, but exact amount TBD by our final calculations – I will submit separate notes on this later). From different accounts, I have heard that Endicott has high quality brick, but does not recycle material. From Endicott’s account, what they are offering is ‘sustainable’ thin-brick with the following qualities: 14-15% PRE-consumer waste (meaning regular grog), LEED pts, a 1-5 mi. distance from extraction to plant, and the various sustainable qualities that all thin-brick makers may claim.

Note that Nebraska is a long way to ship. The greatest green benefit from the Endicott source is – above and beyond the typical industry thin-brick – a higher likelihood that their brick grog utilizes culled or reject bricks, and that their manufacture is on-site. This is not in my opinion an excellent ‘green’ option.

http://www.Endicott.com

2. Lincoln Andrews at Stiles & Hart Brick Co. in Bridgewater, MA has offered us a donation of one block (~1000 bricks). This manufacturer, who is supplying the dorm restoration at the corner of Mass Ave., has an on-site plant in Bridgewater. Lincoln is no ‘green-guru’ – his bricks come
with no big green label and he has expressed understandable distaste for the double-speak of 'green brick' manufacturers (as outlined above). His kilns utilize coal – clearly not a green fuel resource. However, his apparent knowledge of efficiency in firing and other practical aspects of sustainability was impressive to me, and despite his initial disinterest in donating, he considered that he may learn more about manufacturing alternatives from our pragmatic study. The benefits of on-site production and local distribution (only ~25 miles from Cambridge) are undeniable.

There is one green option with Stiles & Hart. John – I will especially need you to advise on this. S&H produce a type of unfired thin-brick: kiln-dried by heat-exchange from their firing kilns, but NOT fired brick. This is like an adobe thin-brick, according to Lincoln, with a high compressive strength and a low modulus. It may break more readily during installation, and he has even said that this may be more of a pain then its worth. But it is clearly an option worth investigating – and I am not in a position to know whether or not this could be acceptable.

http://www.StilesandHart.com

3. This just in – this green brick is the real deal! The chances that this company could supply a thin-brick for us in time for the MIT exhibition is next to impossible – short of some miracle – but it could definitely be possible to work with them for the Cooper-Hewitt exhibition.

James Kolodziey, the president of Green Leaf Brick in Charlotte, NC, supplies all of the raw clay material for the bricks they make, and is in partnership with Charles Taylor and Taylor Brick Co., who does all their firing. A 2007 start-up, Green Leaf only started testing their post-consumer ceramic waste in Taylor’s thin-brick production about 8 months ago, so they are by no stretch engaging in industrial scale production.

Green Leaf’s bricks are 100% recycled material, a whopping 31% post consumer recycled material - most of which, according to James, is actually raw sewage – yes, the shit-brick! They have redirected many a waste stream, utilizing among other things, recycled glass, pure silica from dust collection and air filter receptacles, designated recycle receptacles from large scale ceramic operations, and other perfectly good ceramic material directed towards landfills. Their plastic clay body comes from sand-mining operations, which pull out embedded deposits of clay material (this is normally high pressure washed, discarded, or replaced back into mining pits) – there is an incredible amount of embodied energy in the mining of this excellent clay byproduct. Additionally, his clay body production is embellished with some very serious technology he has developed from carboxy-methyl-cornstarch research in the oil-gas industry, making a stronger ceramic brick with a higher yield and an ASTM C216 severe weather rating. Their clay engineering is quite remarkable, and is extremely fastidious: As James said, “It only takes one tin can to kill a composition.”

Their partner in manufacturing, Taylor Clay, is one of the first manufacturers utilizing an emissions scrub (only 18% of manufacturing operations use this) – a limestone scrubber or kiln exhaust control to remove hydrogen fluoride (EPA synthetic minor, as opposed to Title V emissions). Their fuel source is a byproduct of refined petroleum, petroleum coat, a material with a higher BTU than natural gas, which necessitates advanced air stream techn. for blending and a very effective air scrubber for emissions.

7-DAY MORTAR COMPRESSION TESTING
for the Free Form Vault - Triennial 09 Project Number 0981102A

April 2, 2010

MIT Masonry Research Group
Lab Report: Lara Davis
Material Testing Laboratory, MIT Department of Civil & Environmental Engineering
Laboratory Technician: Stephen Rudolph

INTRODUCTION:
The objective of these laboratory tests is to verify the material strength of Hydrocal® White Gypsum Cement, the fast-setting, high-compressive strength plaster mortar used by the MIT Masonry Research Group for the Free Form Vault, which was built at the Cooper-Hewitt during the week of March 22 – 26, 2010. In comparing our test values to the material specifications of Hydrocal, and drawing also on our previous analysis of the compressive stress within the vault, the goal of the analysis is to verify that the compressive strength of the material greatly exceeds the actual stresses in the vault.

REFERENCE TO ASTM STANDARDS:
Designation: C39/C39M – 09a
Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

Designation: C 472 – 99 (Reapproved 2009)
Standard Test Methods for Physical Testing of Gypsum, Gypsum Plasters and Gypsum Concrete

STATEMENT OF TESTING PROCEDURE:
The testing procedures for 2 inch diameter cylindrical plaster specimens, samples of cured USG Hydrocal White gypsum cement, have followed the procedures referred to by ASTM C39/C39M – 09a and ASTM C 472 – 99 (Reapproved 2009). The date of test was scheduled for a 7-day break of the samples, to insure that the samples were fully cured. The samples were released from the molds 5 days before testing to insure that all free-water in the samples had been released.
The primary difference between the tests which must be performed for these samples and the ASTM designation C 472 – 99 (Standard Test Methods for Physical Testing of Gypsum, Gypsum Plasters and Gypsum Concrete), is that the tested samples are cylindrical specimens and not cube specimens as referred to by this standard. With respect to the method of compressive testing for cylindrical samples, ASTM C39/C39M – 09a will outline procedure. All additional procedures with respect to the testing of plaster material will be covered by C 472 – 99 (Reapproved 2009).

The testing procedure for plaster cylinders differ from that of concrete cylinders primarily in the preparation of the testing surfaces of the cylinders. As plaster cannot be capped by the same methods as concrete cylinders, the most effective method for preparing testing surfaces is to level the upper and lower bounds of the samples with a belt sander. The samples were carefully checked to insure that the surfaces were within a 0.5 degree tolerance from perpendicularly (approximately equivalent to 1mm in 100mm [0.12 in. in 12 in.]), as specified by ASTM C39/C39M – 09a (Section 6.2, page 4).


Date of Testing: 4/2/2010
**DATA:**

<table>
<thead>
<tr>
<th>#</th>
<th>Sample (date/ time)</th>
<th>Mean Height (in)</th>
<th>Mean Diameter (in)</th>
<th>Area (in^2)</th>
<th>Load (lbs)</th>
<th>Peak stress ( \sigma = \frac{\text{Force}}{\text{Area}} ) (psi)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>03/23/10 18:00</td>
<td>3.95</td>
<td>2.02</td>
<td>3.19</td>
<td>9208.1</td>
<td>2888.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>03/24/10 10:00</td>
<td>3.92</td>
<td>2.01</td>
<td>3.19</td>
<td>10164.2</td>
<td>3190.8</td>
<td>Minor surface defects</td>
</tr>
<tr>
<td>3</td>
<td>03/24/10 11:00</td>
<td>3.06</td>
<td>2.02</td>
<td>3.19</td>
<td>9081.65</td>
<td>2848.9</td>
<td>Moderate surface defects</td>
</tr>
<tr>
<td>4</td>
<td>03/24/10 12:00</td>
<td>3.95</td>
<td>2.01</td>
<td>3.18</td>
<td>10972.9</td>
<td>3448.1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>03/24/10 14:00</td>
<td>3.93</td>
<td>2.01</td>
<td>3.17</td>
<td>9310.8</td>
<td>2934.5</td>
<td>Moderate surface defects</td>
</tr>
<tr>
<td>6</td>
<td>03/24/10 15:00</td>
<td>3.93</td>
<td>2.02</td>
<td>3.19</td>
<td>10485.3</td>
<td>3288.8</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>03/24/10 16:00</td>
<td>3.93</td>
<td>2.02</td>
<td>3.19</td>
<td>8791.9</td>
<td>2755.7</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>03/25/10 10:00</td>
<td>3.92</td>
<td>2.01</td>
<td>3.18</td>
<td>9172.6</td>
<td>2884.4</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>03/25/10 11:00</td>
<td>3.92</td>
<td>2.02</td>
<td>3.21</td>
<td>11135.7</td>
<td>3499.7</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>03/25/10 12:00</td>
<td>3.95</td>
<td>2.01</td>
<td>3.17</td>
<td>9424.9</td>
<td>2656.8</td>
<td>Sub-surface air inclusions.</td>
</tr>
<tr>
<td>11</td>
<td>03/25/10 14:00</td>
<td>3.94</td>
<td>2.01</td>
<td>3.17</td>
<td>7137.6</td>
<td>2253.1</td>
<td>Significant sub-surface air inclusions, low peak stress. NOT INCLUDED IN MEAN PEAK STRESS.</td>
</tr>
<tr>
<td>12</td>
<td>03/25/10 15:00</td>
<td>3.96</td>
<td>2.01</td>
<td>3.18</td>
<td>8886.9</td>
<td>2792.6</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>03/25/10 16:00</td>
<td>3.96</td>
<td>2.01</td>
<td>3.18</td>
<td>8629.1</td>
<td>2717.8</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>03/26/10 10:00</td>
<td>3.92</td>
<td>2.01</td>
<td>3.18</td>
<td>11156.9</td>
<td>3513.4</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>03/26/10 11:00</td>
<td>3.94</td>
<td>2.01</td>
<td>3.17</td>
<td>9367.8</td>
<td>2954.6</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>03/26/10 14:00</td>
<td>3.97</td>
<td>2.01</td>
<td>3.18</td>
<td>9534.6</td>
<td>2996.6</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>03/26/10 15:00</td>
<td>3.95</td>
<td>2.01</td>
<td>3.18</td>
<td>8975.2</td>
<td>2822.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Mean Value:</strong></td>
<td><strong>3.94</strong></td>
<td><strong>2.01</strong></td>
<td><strong>3.18</strong></td>
<td><strong>9561.1</strong></td>
<td><strong>3010.2</strong></td>
<td></td>
</tr>
</tbody>
</table>
RESULTS:

Lowest peak stress = 2,253 psi
Highest peak stress = 3,513 psi
Mean peak stress value = 3,010 psi

One sample with very poor mortar distribution was discarded from the final mean value. Significant sub-surface air bubble inclusions were present at the failure crack locations, and this sample yielded a relatively low peak stress value of 2,253 psi.

ANALYSIS:

The material specifications for Hydrocal White indicate that a 1-hour compressive strength should reach 1000 psi, and that the dry compressive strength should reach 5,000 psi (for 45 parts water/ 100 parts plaster). Please reference: Hydrocal Brand White Gypsum Cement, Product Data. The results of our testing showed that the mortar did not achieve the strength predicted by the manufacturer, yielding a lower mean compressive value of 3,010 psi. We believe this is due to 1) Higher water content in the mix, and 2) Insufficient curing. Seven days were allowed for the samples to cure before testing. The samples were removed from the molds four days before testing to allow them to reach their dry compressive strength. It is reasonable to predict, however, that a 14-day break would have resulted in peak stresses closer to the material specifications of USG Hydrocal White gypsum cement.

CONCLUSIONS:

Our structural calculations show that the maximum compressive stress in the Free Form Vault is 11 psi (analyzed for a 1-foot strip of the vault, with a brick thickness of 1.5 inches). Please reference: “Graphic Equilibrium Analysis” and “Structural Analysis for Vault 201” (submitted to Silman Associates). The average compressive strength of the brick is approximately 16,000 pounds per square inch. The average compressive strength of Hydrocal mortar was tested to be approximately 3,010 pounds per square inch. Therefore, the strength of the brick and mortar combined can conservatively be assumed to be 3,010 pounds per square inch, due to mortar as the weaker material. For the applied compressive stress of 11 pounds per square inch, the safety factor against crushing is over 250, and therefore the compressive strength of the vault is at least 250 times stronger than its internal stresses.

Though our tested compressive values of Hydrocal are lower than the material strength indicated by the manufacturer – on account of higher water content in the mix and insufficient curing – the results nevertheless demonstrate the existence of significant safety factors, such that crushing will not occur in the vault. The results of our material tests show that the compressive strength of the mortar is still more than 250 times greater than the maximum calculated stress in the vault, and that the vault will not fail due to weakness of the mortar.
The 4-Dimensional Masonry Construction
MIT MArch Thesis Exhibition
On-Campus Installation Proposal

Index

A1 Construction and Safety Protocol
A 1.1 Introduction, Construction Process Overview
A 1.2 Safety Precautions and Protection Measures, Miscellaneous Requirements and Measures
A 1.3 Notes on Loads and Materials, Student Experience

A2 Preliminary Design Drawings
A 2.1 Perspective
A 2.2 Plans, Sections, Elevations
A 2.3 Details
A 2.4 Site Plan

A3 Mortar Specifications
A 5.1 Plaster Testing Report, page 1 and 2
A 5.2 Plaster Testing Report, page 3 and 4
A 5.3 United States Gypsum Company MSDS for proposed hydrocal, page 1 and 2
A 5.4 United States Gypsum Company MSDS for proposed hydrocal, page 3 and 4
A 5.5 United States Gypsum Company MSDS for proposed hydrocal, page 5 and 6
A 5.6 United States Gypsum Company MSDS for proposed hydrocal, page 7 and 8
A 5.7 United States Gypsum Company Hydrocal White Product Data sheet, page 9 and 10

A4 Brick Specifications
A 6.1 Grean Leaf Brick MSDS for proposed brick, page 1 and 2
A 6.2 Grean Leaf Brick MSDS for proposed brick, page 3 and 4
A 6.3 Grean Leaf Brick MSDS for proposed brick, page 5 and 6
A 6.4 Photographs of samples of Grean Leaf Brick

Design & Builder
Lara K. Davis, MIT Masters of Architecture Candidate 2010

Advisors
John Ochsendorf, Associate Professor of Civil Engineering & Architecture, MIT
Nader Tehrani, Professor of Architectural Design, MIT
Mark Jarzombek, Professor of History, Theory and Criticism, MIT

E-15 VAULT
MIT Masonry Research Group
Lara K. Davis

MIT Dept. of Architecture
77 Massachusetts Ave.
Cambridge, MA 02139
646.662.5424 tel

INDEX

In Situ Constructed Masonry Vault
04.22.10
MIT FACILITIES PROPOSAL:
E-15 VAULT
MIT
Masonry Research Group
Lara K. Davis

MIT Dept. of Architecture
77 Massachusetts Ave.
Cambridge, MA 02139
617.253.4424 tel

04.22.10 Site Plan
In Situ Constructed
Masonry Vault
04.22.10
Plan, Sections, Elevation

In Situ Constructed Masonry Vault

04.22.10
1. **DETAIL OF PLYWOOD BEARING PAD**

   SCALE: 1 1/2" = 1'-0"

2. **DIAGRAM OF PRIMARY CATENARY LINES**
Perspective
In Situ Constructed Masonry Vault
MARVIN E. GOODY STATEMENT:
I feel, rather humbly, that this proposal generously meets the criteria of selection for the Marvin E. Goody prize. Marvin Goody's innovative, experimental work – including the House of the Future, which he developed while teaching alongside Buckminster Fuller at MIT – seemed to be somehow balanced by the traditional building craftsmanship and preservation aspects of his design practice with John Clancy and Joan Goody. I think that such architects prove that innovation is not merely blind forward-thinking, rather complex re-piecing of the best technologies available to our industry, culled from a pool of speculative new technologies and a counterpart in established, empirically tested knowledge bases and constructional logics. Contemporary architectural practice often provokes polarizing declarations – traditional technologies are anachronistic, or experimental technologies are improbable or remote. Perhaps, as a young architect, my experience is insufficient to well argue the subtle areas of such distinctions; though I admit that I do not actually believe in the value of such totalizing declarations. I do, however, feel that it is in my purview as a student to follow through in developing my past professional experience in construction with traditional building materials and techniques, and to pursue the disciplinary research which engages this technological divide between past and future construction-design methods.

I also feel that it is my responsibility to utilize all of the resources that I have available to me here at MIT, which extend both internationally through scholarship and to our local context of Cambridge through practice. I think that I may best address the applicability of the Goody’s vision to this project by referring to some of the local Cambridge industry overlap which was generated through one of the critical projects in the development of this thesis – the first vault prototype built in September. When our group of young designers set out to build this vault, the Boston-based branch of the International Masonry Institute sent over one of their masons of 40 years experience, to share knowledge sets, to learn about this Catalan vaulting technique, and to himself climb the ladders to assist in building. Outreach to the local contracting community resulted in the support of our project by representatives of the Local 40 Carpenters Union, local distributors, and other major contractors at MIT construction sites, who critically enabled our project by providing us with post-consumer contractors’ waste towards the construction of our form-work. Most impressive was the experience of visiting the only remaining brick manufacturing plant in Massachusetts, the 4th generation manufacturer Stiles & Hart, and the sense of mutual respect developed as I ogled their traditional beehive kilns, while they stared with some perplexity at images of our experimental vault form. All of these industry workers participated fundamentally in enabling this vault – with a sense of pride and value in the exchange. They reminded me of why I came here, and of my first experience of MIT – driving a masonry contractor’s truck, well laden with palettes of bricks, past jay-walking students and the dome of 77 Mass Ave. One may nod to the building industry for their role in facilitating academic research projects such as these, but it is quite honestly the building industry to which I owe my being here in the first place.
GOODY RESEARCH PROPOSAL:

This grant would make possible the construction of an innovative structural masonry prototype and the development of my knowledge base in the building of extremely thin-shell vaults. The novelty in this research is that it proposes to utilize both experimental structural engineering software and traditional masonry construction technologies – together – towards the goal of innovative design, engineering and construction. These computational technologies have enabled structural form-generation which radically departs from the typical constraints of traditional masonry construction; however, what I have discovered – through several ongoing masonry research projects with MIT Professor John Ochsendorf and ETH Professor Philippe Block – is that these technologies still deeply rely on traditional, constructional practices and methods to realize them. Once the structural analysis enabled by these design tools is grounded in the techniques and the constraints of masonry constructibility, it will allow us to build within a new paradigm of constructible vaults, innovative parallels of which may be seen in the work of Eladio Dieste and Rafael Guastavino.

This research will manifest in the construction of a full scale structural masonry vault prototype, scheduled to be built in the MIT N51 courtyard in conjunction with my thesis presentation in early May 2010. This vault will be the last in a series of vault prototypes, one of which will be presented in the public context of the Cooper Hewitt’s International Design Triennial in May (built in March). The first prototype, already completed this past September through support from the MIT Museum Students’ Night program, was a total success in that – through its complete collapse – we thoroughly educated ourselves about many of the critical limits involved in such constructions. The construction of these earlier prototypes will have enabled my design and construction team, a collection of 7 MArch students, to fully develop the material research, construction sequencing design and the masonry construction techniques, which will critically inform my Spring thesis vault.

Beyond the explicit aim of this project to present contemporary masonry innovation at MIT to the greater public, the research in these construction methods is integral to my design thesis, “Phase Change Morphology: 4 Dimensional Construction for Disaster Response”. The technical goal of the thesis is to develop an innovative system of translational, construction-design drawing, which – as previously stated – will link construction methods in traditional masonry craftsmanship with methods in contemporary computational design. This will rely on scholarship of historical precedents of masonry ‘design drawing’ that suggest ways in which design drawings transmitted and translated information between Islamic mathematicians, architects, master masons and masonry craftsmen. This study has been pursued under the supervision of Gülru Necipoglu of Harvard History of Art & Architecture, and will culminate in research travel that is scheduled for early January. The thesis will then investigate design drawing as a new type of sequenced construction drawing, a theory to be tested by translating it, as praxis, into a built masonry prototype. By reinserting concerns of constructibility – material, tectonic and sequencing – into the contemporary design drawing, the desired impact is the establishment of a more mutualistic relationship between the design, engineering and construction sectors of our discipline.
BIBLIOGRAPHY:

STRUCTURAL MASONRY:

GEOMETRY & THE 4th DIMENSION:

ILLUSTRATION CREDITS:

All illustrations by the author unless noted below. Listed by section and page number (left to right):

1.1 Pine’s Calyx, Documentation Courtesy of Michael Ramage. ................................................................. 12
1.2 Pine’s Calyx, Documentation Courtesy of Michael Ramage. ................................................................. 12
1.3 Eladio Dieste: Innovation in Structural Art, Stanford Anderson, Construction with quick-setting plaster, p. 203. ................................................................. 12
1.4 Eladio Dieste: Innovation in Structural Art, Stanford Anderson, Vault supported load 4 hours after construction, p. 203. ................................................................. 12
1.5 Pine’s Calyx, Documentation Courtesy of Michael Ramage. ................................................................. 12

2.1.1 The Projective Cast, Robin Evans, Peterborough Cathedral, retrochoir, p. 233. ................................. 16
2.1.2 Eladio Dieste: Innovation in Structural Art, Stanford Anderson, Cadyl Horizontal Silo, Young, 1976-78, Stanford Anderson, p. ................................................................. 16
2.1.3 The Old World Builds the New, “First Church of Christ Scientist: Staircase under construction, New York, NY, 1903”, p. 30. ................................................................. 17
2.1.4 The Old World Builds the New, “Quackenbush Building: Section of Stairwell, Paterson, NJ, July 30, 1902”, p. 59. ................................................................. 17
2.1.5 The Old World Builds the New, “St. Joseph’s Seminary: Stairs under Construction, 1892”, p. 51. .......... 17
2.1.6 Félix Candela: Engineer, Builder, Structural Artist, David Billington, San Felipe de Jesus Church, Cuernavaca, Mexico. ................................................................. 17
2.1.7 Félix Candela: Engineer, Builder, Structural Artist, David Billington, San Felipe de Jesus Church, Cuernavaca, Mexico. ................................................................. 17
2.1.8 Félix Candela: Engineer, Builder, Structural Artist, David Billington, San Felipe de Jesus Church, Cuernavaca, Mexico. ................................................................. 17
2.1.9 Eladio Dieste: Innovation in Structural Art, Stanford Anderson, Citricos Caputto Fruit Packing Plant, Salto, 1986-87, p. 83. ................................................................. 17
2.1.13 Antoni Gaudí, Colónia Güell, Barcelona. ................................................................. 17
2.1.14 IL 34, Frei Otto et al., Antoni Gaudí, Hanging model, Colònìa Güell, Barcelona, p. 115. ....................... 17
2.1.15 IL 34, Frei Otto et al., Antoni Gaudí, Crypt, Colònìa Güell, Barcelona, p. 184. ................................................................. 17

2.2.1 Green Leaf Brick, Photos Courtesy of James Kolodziey. ................................................................. 18
2.2.2 Green Leaf Brick, Photos Courtesy of James Kolodziey. ................................................................. 18
2.2.3 Green Leaf Brick, Photos Courtesy of James Kolodziey. ................................................................. 18
2.2.4 Tara Donovan, Untitled. ................................................................. 19
2.2.5 Tara Donovan, Untitled. ................................................................. 19
2.2.6 Shigeru Ban, ed. Matilda McQuaid, Paper tubes, p. 13. ................................................................. 19
2.2.7 Shigeru Ban, ed. Matilda McQuaid, Japan Pavilion, Expo 2000, Hannover, Germany, 2000, p. 65. ............................................................................................................. 19
2.2.8 Rural Studio: Samuel Mockbee and An Architecture of Decency, Andrea Oppenheimer and Timothy Hursley, p. 101. ................................................................. 19
2.2.9 Photo Courtesy of Sara Riley, The Copicut Cleanup, Fall River Watershed, 2009. ................................................................. 19
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Author(s)</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.1</td>
<td>Form and Forces: Designing Efficient, Expressive Structures</td>
<td>Diagram redrawn from John Ochsendorf, Structural limits in corbelling</td>
<td>22</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Flicker photograph, Istefan TM, Dresden Synagogue</td>
<td>Wandel Hoefer Lorch + Hirsch architects</td>
<td>22</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Gaudi: Completed Works, Isabel Artigas, Columns, Teresian School</td>
<td>Antoni Gaudi, p. 190</td>
<td>22</td>
</tr>
<tr>
<td>3.1.4</td>
<td>Gramazio + Kohler</td>
<td>......................................................</td>
<td>22</td>
</tr>
<tr>
<td>3.1.5</td>
<td>Gramazio + Kohler</td>
<td>......................................................</td>
<td>22</td>
</tr>
<tr>
<td>3.1.6</td>
<td>Office dA, ed. El-Khoury and Ojeda, Casa la Roca</td>
<td>Caracas, Venezuela, p. 99</td>
<td>22</td>
</tr>
<tr>
<td>3.1.7</td>
<td>Gramazio + Kohler</td>
<td>......................................................</td>
<td>22</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Living Architecture: Ottoman, Ulya Vogt-Göknil, Yeschil Mausoleum and Mosque</td>
<td>Stalactite dome, Bursa, p. 71</td>
<td>24</td>
</tr>
<tr>
<td>3.2.2</td>
<td>The Topkapi Scroll</td>
<td>Gülru Neçipoğlu, Projection from Mucarnas plan to section</td>
<td>24</td>
</tr>
<tr>
<td>3.2.3</td>
<td>The Topkapi Scroll</td>
<td>Gülru Neçipoğlu, Plan of Mucarnas</td>
<td>24</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Gaudi Unseen: Completing the Sagrada Familia, Mark Burry</td>
<td>Drawing of hyperboloid constructions, Sagrada Familia, Barcelona, p. 104</td>
<td>24</td>
</tr>
<tr>
<td>3.2.5</td>
<td>Gaudi Unseen: Completing the Sagrada Familia, Mark Burry</td>
<td>Drawing of hyperboloid constructions, Sagrada Familia, Barcelona, p. 104</td>
<td>24</td>
</tr>
<tr>
<td>3.2.6</td>
<td>Gaudi Unseen: Completing the Sagrada Familia, Mark Burry</td>
<td>Drawing of hyperboloid constructions, Sagrada Familia, Barcelona, p. 104</td>
<td>24</td>
</tr>
<tr>
<td>3.2.7</td>
<td>Gaudi Unseen: Completing the Sagrada Familia, Mark Burry</td>
<td>Nave detail, Sagrada Familia, Barcelona, p. 52</td>
<td>24</td>
</tr>
<tr>
<td>3.2.8</td>
<td>Gaudi Unseen: Completing the Sagrada Familia, Mark Burry</td>
<td>Nave detail, Sagrada Familia, Barcelona, p. 52</td>
<td>24</td>
</tr>
<tr>
<td>3.2.9</td>
<td>Gaudi Unseen: Completing the Sagrada Familia, Mark Burry</td>
<td>Fragment of vaulted ceiling hyperboloid, Sagrada Familia, Barcelona, p. 49</td>
<td>24</td>
</tr>
<tr>
<td>3.2.10</td>
<td>The Projective Cast, Robin Evans</td>
<td>Redrawn trait for the trompe at Anet, Premier Tome, Philibert Delorme, p. 185</td>
<td>25</td>
</tr>
<tr>
<td>5.1</td>
<td>Photo Courtesy of the Cooper-Hewitt, Vault 201, The MIT Masonry Research Group</td>
<td>......................................................</td>
<td>47</td>
</tr>
<tr>
<td>6.1</td>
<td>Symmetries of Islamic Geometrical Patterns</td>
<td>Syed Jan Abas, Pattern symmetry translations diagram, Redrawn</td>
<td>56</td>
</tr>
</tbody>
</table>