CATALAN VAULTING IN ADVANCED MATERIAL:
NEW APPROACHES TO CONTEMPORARY COMPRESSIVE FORM

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Submitted to the Department of Architecture in partial fulfillment of the requirements for the degree of Master of Architecture at the Massachusetts Institute of Technology
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ABSTRACT

The translation of traditional building methods to modern construction techniques offers unexplored opportunities for material and form in architecture. Recent innovations in cellular ceramics married with traditional timbrel vaulting suggest a new approach to compressive form in structural masonry spans. Research into the history and construction of timbrel vaults and the material properties of cellular ceramic masonry shows that they are well-suited to one another. Building timbrel vaults with aerated autoclaved concrete (AAC) brings to architectural practice a new family of economically viable, expressive configurations of structural spans in masonry.

The Catalan masonry technique, also referred to as timbrel or Guastavino vaulting, allows thin structural spans to be built without the use of supporting formwork. Once widely used in American construction, the technique is now little-known. This thesis documents the recent construction of two 11.3m (37') domes in England and structural research into building timbrel vaults with AAC tile. An artist’s studio designed based on the information gained demonstrates the renewed feasibility of building expressive masonry structures. The techniques used to design and build structural masonry spans show that merging modern materials with traditional craft capitalizes on the significant strengths of each. These new buildings demonstrate the economic efficiency and formal viability of timbrel vaulting in contemporary architecture.

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MHR
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INTRODUCTION

The translation of traditional building methods to modern construction techniques offers unexplored opportunities for material and form in architecture. Recent innovations in cellular ceramics married with traditional timbrel vaulting suggest a new approach to compressive form in structural masonry spans. Research into the history and construction of timbrel vaults and the material properties of cellular ceramic masonry shows that they are well-suited to one another. Building timbrel vaults with aerated autoclaved concrete (AAC) brings to architectural practice a new family of economically viable, expressive configurations of structural spans in masonry.

Catalonia and its capital, Barcelona, became a center of masonry architecture, thanks to the genius of Antoni Gaudi and the work of other builders and architects such as Rafael Guastavino, Josep Puig i Cadafalch, César Martinell, Lluís Muncunill, Lluís Domenech i Montaner, and the masons of the Catalan tradition. These men applied their structural knowledge to terracotta tiles and plaster mortar to arrive at previously unimagined forms. In the spirit of these pioneers, this thesis explores timbrel vaulting with advanced materials, using aerated autoclaved concrete, a lightweight cellular ceramic that has never been applied to vaulted constructions. In addition to its low density, AAC has other advantages for vault construction which include strength appropriate to the stresses in masonry spans; a rough surface well-suited to the application of mortar; and good insulating and acoustical properties.

Timbrel vaulting has a long history in the Mediterranean region, particularly in Spain. It was used to such an extent in Catalonia that it is widely known as Catalan vaulting, but it is a building practice in many parts of Spain. Catalan vaulting was extended as a large-scale building technique in the 1860s by Rafael Guastavino, a Spanish architect and builder who later brought the technique to the United
States.¹ In the US, Guastavino patented the construction method and employed it in a wide range of public and private buildings, working as a contractor for the most well respected architects of the early 20th century. Because of this legacy, the technique is sometimes referred to as Guastavino vaulting.

Thin ceramic tiles and fast-setting gypsum mortar are the hallmark of timbrel vaults wherever they are built. In the hands of skilled masons the technique allows thin structural spans to be built without the use of supporting formwork. By replacing traditional brick or terracotta with tiles made from AAC, the approach of this thesis is not to design a building and then determine how to build it, but rather to explore the limits of construction, to establish what can be designed, and to determine what are the advantages of the change in material.

Vaulting has been highly successful in creating elegant masonry spans throughout history. The Uruguayan engineer Eladio Dieste said

The resistant virtues of the structures that we seek depend on their form; it is through their form that they are stable, not because of awkward accumulation of material. There is nothing more noble and elegant from an intellectual viewpoint than this: to resist through form. ²

Buildings constructed in the timbrel tradition exhibit just this ideal; they are elegant expressions of structure and form. In the late 19th and early 20th century, hundreds of years of structural brick construction developed into new forms that had not been imagined in the pre-Industrial era. This thesis takes that construction method and compressive form, both firmly rooted in the bond between good design and good building, into the 21st century.

Catalan-vaulted passageway in the streets of Girona
History

The specific origin of timbrel vaulting is unclear, but the greatest concentration and variety of bóvedas tabicadas, as they are known in Spanish, can be found in Catalonia. The medieval streets of Girona, the rural fields of Catalonia’s Terra Alta, and the industrial complexes around Barcelona are all home to a wonderful array of vaulted buildings. These buildings, and the work of the people who designed and constructed them, serve as the foundation for further development of timbrel vault construction.

In the latter half of the 19th century in Spain, the vernacular tradition of Catalan vaulting was being developed and applied to industrial building. Rafael Guastavino first used it on a grand scale in the Batllo textile factory (1869). Advertised as a fireproof method of construction, a significant advantage,

[j]t attracted a great deal of attention from architects and instructors at the [Barcelona] School of Architecture, who visited often during construction. These tile-and-mortar vaults were a traditional method of construction, but according to Guastavino’s writings, 99 percent of the architects and builders had not heard of it. He revived it with other architects working in Barcelona in the 1860s and 1870s.3

Among the other architects who would make the masonry of Catalonia famous were Antoni Gaudi, Lluís Domenech i Montaner, and Josep Puig i Cadafalch.4 Their work is closely associated with Catalonian Modernismo, an aesthetic, social, and political movement that coincided with and has close ties to Art Nouveau. Guastavino

brought the masonry technique to the United States in 1881, where he collaborated with many of the most noted architects of the time, such as McKim Mead and White, Cass Gilbert, Carrère and Hastings, among many others, to build some of the great spaces of the 20th century. Among these buildings are Boston Public Library (1900), Pennsylvania Station (1908), Grand Central Terminal (1909), and the dome of St. John the Divine (1899-1935). Guastavino’s company built more than 1000 buildings using his Catalan construction system, but it eventually succumbed to the combined pressures of Modernism, which shunned the vault, and economics, as rising labor costs made masonry vaulting unable to compete with steel-framed buildings. Guastavino’s techniques have faded from the landscape of American construction, but they are still in use today in Spain.

Timbrel-vaulted buildings can be found in any size in Catalonia, but their greatest commercial application was in industrial and agricultural buildings. The economy with which they could be constructed served the need for large spaces associated with industrial output and agricultural production. Among the largest and most attractive is the vaulted roof of the steam-powered textile factory of Aymerich, Amat i Jover in Terrassa by Lluís Muncunill (1907-1908), which covers 11,000 m² (118,000 ft²). The building has been restored and now serves as a museum of science and industry. Despite its immense size (a roofed area of more than two football fields), the structural form and the visible masonry unit lend the space a humanity that makes it approachable.

The agricultural cooperatives designed by César Martinell continue a tradition of economic construction and expressive architecture. He built warehouses, wineries, and agricultural factories throughout

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5 The records of the Guastavino Company are held in the Guastavino/Collins archive at Columbia University and are searchable via http://clio.cul.columbia.edu/
3 Roof and interior of Aymerich, Amat i Jover textile factory
Interior of Sant Guim de Freixenet warehouse
southwest Catalonia between 1918 and 1956, many of which are distinguished by graceful funicular ribs, vaulted roofs, and exquisite masonry details. A large number are still in use. Martinell’s warehouse in Sant Guim de Freixenet (1920) exhibits an elegant combination of arches with shallow timbrel vaulted spans between them, making this utility building far from merely utilitarian. His careful attention to detail is evident in the structure of the Cooperativa Agrícola de Gandesa, where the ribs thicken by one tile at each intersection with the vertical piers that transfer loads from the roof.

The well-considered application of structural elements creates a utility of space without the utilitarianism associated with contemporary factory buildings. Today’s steel frame buildings may be inexpensive to purchase and quick to assemble, but they often leave us little to cherish or admire about them. The qualities for which people choose vaulted structures in the first place, such as good light, strength, longevity, clear spans, and ease of construction and modification, are the same qualities that ensure their continued use once they have outlived their original purpose. Many buildings commissioned originally as factories are now living a second life. Among them are the immense Caxia Forum in Barcelona, once a thread factory and now an art museum, and the former bottling plant of the Codorniu cava estates which serves now as the winery’s museum and reception hall. Both were designed by Josep Puig i Cadafalch and are reminders of the value in preserving and reusing good buildings.

The work of these architects and the rich history of timbrel vault construction stand as examples from which we can draw lessons in space and structure for designing and building good compressive form today.

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Construction

In addition to the rich history of vaulted buildings, an understanding of their design and construction is necessary for meaningful development of the technique. This comes both through research and from direct involvement in design and construction. Throughout 2005 Prof. John Ochsendorf, Wanda Lau, and I collaborated with British designers, engineers, and masons to design and construct the first timbrel-vaulted building in England.\(^9\) The Pines Calyx™, as the building is called, was a remarkable opportunity where timbrel vaulting and traditional techniques of design could be updated to build an entirely contemporary conference center.

The Pines Calyx roofs are two shallow spherical domes supported by concrete ring beams on top of chalk walls. The domes are constructed of three layers of ceramic tile with intermediate layers of Portland cement mortar giving a total structural thickness of 100mm (4’’). Each dome spans 11.3m (37’) with a rise of 1.33m (4.3’) at the center. In addition, each dome has a circular oculus tapering upward to 1.6 m in diameter and a lens-shaped opening on one side. The opening of the upper dome is supported by steel struts inserted between the dome and the ring beam. The opening in the lower dome is supported by the wall of the upper dome.

The Pines Calyx is an ecological conference center set in the organic Pines Gardens of St. Margaret’s Bay, nestled in the White Cliffs of Dover, England, constructed for the St. Margaret’s Bay Trust. The main design is by Isaac Benjamin and Alistair Gould of Helionix Designs. Philip Cooper of CameronTaylor engineered the building, with structural analysis of the domes done at MIT. Paul Mallion of Conker Conservation served as the contracts administrator. The general contractor, Andrew Bassant of Eco-librium Solutions, worked closely with me as manager of the dome construction, Sarah Pennal,\(^9\)

\(^9\) “UK sees its first use of Guastavino vaulting” *New Civil Engineer*, 4 August 2005 p 12.
the head English mason, and Maximo Portal and Fernando Marin, head masons from Spain who came to teach and to build.

When designing the domes of the Pines Calyx, we relied on the same principles and constraints used by earlier vault builders. Timbrel vaults in Catalonia and elsewhere are built of unreinforced masonry, with steel ties to take tension where necessary. Rafael Guastavino argued in his essay “Cohesive Construction”10 that his patented building method (which was essentially a large-scale application of Catalan vaulting in the United States) could support the bending moments of structural loads. In fact, timbrel vaulting, like all other types of unreinforced masonry, can only support axial loads in compression.11

These axial loads made the structural design of vaults well-suited to analysis with graphic statics, the prevailing technical calculation method at the time. Antoni Gaudi, César Martinell and Rafael Guastavino made extensive use of graphic calculations in their work,12 which gave them the ability to build larger and more safely than empirical design in use at the time would allow.13 A structural solution found using graphical statics shows one path the forces will follow in the structure and can thus help shape the design. If the resulting line of force lies entirely within the masonry, the structure will stand under the applied loads.

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In the design of the Pines Calyx we verified the safety of the domes during construction and under uniform gravity loads by applying membrane theory, which assumes that no bending occurs and that all forces are carried along the center-line surface of the domes as a combination of hoop forces and meridional forces.\textsuperscript{14} For the case of asymmetrical live loading on the domes, we applied automated graphic statics\textsuperscript{15} to allow us to search for equilibrium solutions for the difficult problem of domes with cut-outs. By building in a traditional manner but analyzing with advanced technology, we were able to specify a thinner shell than would have been built using rules of thumb employed in Spain.\textsuperscript{16} The flexibility of the masonry technique also allowed significant design changes during construction.

The tiles used in the Pines Calyx were locally made by Robus Ceramics using waste clay from a nearby gravel quarry. They are 150mm x 300mm x 25mm (6” x 12” x 1”), and because of their substantial weight an additive, Flolite\textsuperscript{TM}, was mixed with the clay to reduce the weight of the soffit (first layer) tiles from 1.9kg (4.2 lbs) to 1.2kg (2.7 lbs). This weight savings was necessary to build the vaults, although it added significantly to the cost of each tile.

Maximo Portal and Fernando Marin, instructors at the Escuela Taller García de la Huerta IV in Zafra, Spain, came to England with one of their students, Ismail Villar, to teach timbrel vaulting techniques to the British masons. The construction of each dome took two weeks with three masons and four laborers. A detailed method statement by Sarah Pennal, the head English mason, is attached as an appendix; the essential construction sequence is outlined as follows:

\textsuperscript{16} Personal communication with Maximo Portal, July 2005.
Each dome is built on a heavily reinforced concrete ring beam which resists its thrust. The most important part of the construction is making sure the first course is level, circular, and coincident with the sphere of the dome as designed.

We ensured these conditions by using two wires (referred to together as a cintrel), pulled taut and set to the plywood geometric guides. One wire was attached to a rotating collar at the top of the central pole; the other was attached to the base of the pole. When the length of each wire is set to a point on the wooden guides cut to the curve of the sphere, the wires can then be rotated in the space between the guides, perfectly describing one line along the sphere.

Once the first course is established all the way around the base of the dome, the soffit is built up in multiple courses. This is to ensure a consistent and smooth surface, as it is extremely difficult to get a sense of the curvature from only one course of tile work. The mason lays the tile with her assistant cleaning and pointing the plaster mortar immediately. This offers a great time savings in final cleaning once the dome is complete.
As soon as the first layer is built up sufficiently and the ring completed, the second layer is applied at 45° to the soffit, so as to break all joints, and set in cementitious mortar. The mortar is spread over a wide area which the tiles are then bedded into. The bed of mortar is generously thick (~10mm or ½"), as are the joints between the tiles.
Similarly, the third course is added as soon as a ring of the second course is complete. The mortar bed and thickness are the same, and again the tiles are rotated 45° and laid vertically as soldier courses to ensure a break with the joints below. The second and third layer are built up from the outside as the first layer continues to be built from the inside. Once the mortar of the third course is set it can be walked on, greatly facilitating the construction.

At the oculus the courses are measured and set level individually using tiles cut down to accommodate the tighter curvature. Once the dome is complete, the soffit is cleaned using water, trowels, and stiff brushes.

We then added a 20mm (3/4”) thick screed layer of concrete to the entire structure. This added to the structural thickness and provided a smooth surface for application of insulating and roofing material.

The construction of the Pines Calyx domes was revealing in many ways. The tiles we built with were at the outer weight limit of what the gypsum mortar would hold. Because the tiles were handmade, the variability in their size and shape could be frustrating to work with but ultimately lends the space a wonderfully modulated surface in color and texture. Since the timbrel vault construction method requires only geometrical guides, it allowed us greater freedom in the form of the dome during construction than would a method that required complete structural formwork. Thus we could change the shape and details of unbuilt elements of the dome as the main work continued uninterrupted. This was useful at the oculus, where the original design called for a sharp angular break in the surface where the flat dome met the tapering vertical walls of the oculus (see figure 6). This junction was a difficult construction detail and visually awkward. Through discussions with the client and masons, we arrived at and built a more elegant solution of a continuous sweep of the curve from dome surface to oculus wall.
After the completion of the domes, John Ochsendorf and I were asked to design a timbrel-vaulted spiral staircase for the main conference room in the Pines Calyx. We used similar techniques to design the spiral staircase, applying automated graphic statics to the basic form. This allowed us to design a staircase with greater structural expression than would have been possible using conventional design tools.

The Calyx stairs are a single flight of helical stairs from the ground floor to the first floor. The stairs are constructed of three layers of ceramic tile with intermediate layers of Portland cement-based mortar that give a total structural thickness of 120mm. The stairs have a landing in the middle supported by the vaults below. The stair tread and landing locations were set by UK building code. Furthermore, the speciation drawings had already been approved for construction by the local authorities; what remained to design was the supporting structure. Because the stair is directly below the large lens-shaped skylight in the upper dome, we pulled the entire staircase 90mm away from the chalk wall, allowing light to pass behind it. Using the applied forces and load requirements we were able to determine the thinnest possible shell to fit the design constraints.

The success of the Pines Calyx project demonstrates the viability of timbrel vaulting as a contemporary building technique. A growing interest in building methods which lessen the use of concrete or create local opportunities in a global marketplace may signal good news for the future of building timbrel vaults. Already this project has generated follow-on work in South Africa and other promising leads in the United Kingdom.
Lower dome complete, with scaffolding
Material

Aerated autoclaved concrete is a lightweight cellular ceramic that has never before been applied to vaulted construction. Merging traditional timbrel vaulting with lightweight concrete foam exploits the significant advantages of each. Evaluating structural masonry spans in light of the formal, material, and economic possibilities offered by using AAC in place of traditional terracotta bricks suggests the possibility for greater formal variety within a buildable family of structural forms.

AAC is an advanced masonry product typically used in structural walls. It has many advantages in the building trade, including light weight, high R-value, fire resistance, ease of cutting and assembly, and ready-to-finish surfaces. These qualities make AAC an excellent material for building structural form with timbrel vaults. AAC is so light that it floats, and in fact it has roughly the same density as Honduras mahogany.17

AAC properties are governed by ASTM C 1386-98.18 The material for this research was supplied by Trustone America of Providence, Rhode Island. They produce three grades of AAC each of which varies primarily in density and compressive strength. I used the mid-grade TruStone AAC TS 3, which has a density of 37lb/ft³ (560 kg/m³) and a compressive strength of 600 psi (4.14 MPa).19 Due to the cellular nature of AAC, an 8” thick uninsulated wall has an R-value of about 15.20

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17 http://www.simetric.co.uk/si_wood.htm
19 http://www.trustoneamerica.com/properties.html
20 http://www.trustoneamerica.com/thermal.html
AAC is factory-made in a highly controlled environment. The ingredients and mixture are essentially the same as concrete, with the addition of a small amount of powdered aluminum only seconds before the batch is poured into a mold. The aluminum binds to chemicals in the mixture, releasing hydrogen gas which imparts macroscopic bubbles into the “cake.” The resulting product is chemically identical to the naturally occurring mineral Tobermorite.21 The green cake is left to rise for 45 minutes, after which it is run through a wire slice to produce the desired block size, typically 8” x 14” x 24”, although a variety of sizes is available. As soon as the material has been cut, it is moved into an autoclave, where it is cooked at high temperature and pressure for a few hours, after which the product is complete and ready for packing and shipping. The only addition I made to the process was to take the final block product and cut it into 1” and 2” thick tiles for building vaults. If there were a requirement for a large number of tiles for a timbrel-vaulted building project, the cutting wires could be reconfigured to produce 2” thick tiles directly.

A significant advantage to building in AAC is that it can be shaped with conventional woodworking tools. This makes the cuts necessary for tight curvature and complex joints simple, something that cannot be said for brick or terracotta. I used a standard 14” band saw equipped with a carbide-tipped blade (which did not deteriorate due to abrasion from the AAC).

Because AAC is highly porous, bonding it with quick-setting gypsum plaster is more difficult than with standard brick or terracotta, but the resulting bond is stronger. In order to get a good bond, both surfaces to be bonded need to be quite damp, but dry enough that the mortar won’t slide off the tile. I tested US Gypsum Moulding #1 plaster, Hydrocal, and Hydrostone22 for mortars, and found that Hydrocal

21 Personal communication with David Napier, Marketing Director of TruStone America, during a tour of their production line in Vineland, New Jersey.
22 Detailed USG product properties are at http://www.gypsumsolutions.com
gave the best empirical results. It is a stronger material in compression and easier to work with than Moulding #1; Hydrostone doesn’t set fast enough to be very useful. Hydrocal is more expensive than Moulding #1, but its faster setting time makes it a worthwhile choice. In laboratory tension tests across the mortar, however, we determined that on average moulding plaster is stronger, but its strength is spread over a wider range (see detailed discussion below) so Hydrocal is still the better choice.

Conventional wisdom suggests that structural masonry spans have fallen out of favor in part due to their high labor cost. Because bricks are small and spans are relatively large, it stands to reason that labor is a limiting factor. AAC allows the economy of masonry spans to be reconsidered: by using larger unit sizes, the labor costs are lessened while the constructive and formal benefits of timbrel vaulting can be exploited. In experimenting with a number of block thicknesses and sizes, the largest reasonable size for construction is a 16” x 8” x 2” thick tile. In controlled testing a similar tile 1” thick will also work, but at 1” thick AAC is too fragile to be considered a viable building material. As long as the curvature of a given span can be accommodated with this modulus, great economy in construction can be achieved.

The two domes recently finished in England, built with typical 12” x 6” x 1” brick tile, serve as an example of the economy possible using AAC tiles. Averaged over the whole construction, one mason could lay about 7 tiles per hour. At this rate, it took about 924 man-hours to complete the tile work of each dome, to which we added a 1” screed of concrete for the necessary structural thickness. Had we been working with the larger size possible using AAC (16” x 8” x 2”), we would have been able not only to complete each dome in 520 hours (a time savings of 77%), but also to build the required structural thickness in three layers of masonry without the necessity of an additional screed. This would have afforded us an additional savings of 100 man-hours on each dome, in total saving more than £13,500 ($23,750) (at prevailing rates of £15/hr). Add to this the material cost
of AAC tile at about $0.53/ft^2, as compared with almost $7.00/ft^2 for the Pines Calyx domes or $3.56/ft^2 for split brick (9" x 4½" x 1½" – the largest tile-like brick mass-produced in the US) and the cost advantages of using AAC become clear.

<table>
<thead>
<tr>
<th>Material Cost</th>
<th>Build Hours</th>
<th>Labor Cost</th>
<th>Total Cost</th>
<th>£/sf</th>
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<tr>
<td>Robus Tiles (UK)</td>
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<td>TruStone AAC</td>
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<td>£16,000</td>
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Table 1 Construction cost comparison for the Pines Calyx domes

In addition to economy, the versatility of form-making with AAC allows greater freedom in design and construction. While the final form of any masonry structural surface must transfer loads in compression, the configuration during AAC-based construction can deviate from pure compression in a manner that is not possible when building in brick. The light weight and the tensile capacity of the mortar joint allow the possibility of cantilevered vaults during construction, making a wide variety of forms available to the designer and the craftsman.

To illustrate this benefit I built a few studies of non-structural timbrel-vaulted form. These elements are the beginnings of what would be structural forms, but as they are demonstrate some of the significant variety possible when given greater freedom of assembly.

Furthermore, bearing conditions are easy to create, as they require only a close approximation of shape and good mortar contact. One simple 4” wide and 2” thick arch I built spanned 4’ across a corner and could easily support over 200 pounds. It took about 10 minutes to construct.
Because AAC is easily worked with common shop tools, it can be shaped and combined with other elements in manners that would typically be antithetical to brickwork. For elements where tensile capacity is required, it is possible to combine AAC with tension bands made of high-strength steel strapping. This made it possible to create an 8’ span beam in AAC using epoxy as mortar and strapping to constrain the tension.

I also conducted quantitative tests in support of the qualitative research. The goals were to determine bond strength, to see whether AAC fails like typical masonry under load, and the failure patterns of an AAC dome under concentrated crown load.

In preliminary tests, a fresh AAC – mortar joint (using Hydrocal) can only take about 10psi in direct tension. Nevertheless this is enough strength to hold a 5-gallon bucket of water with a 1”x4” joint. This is more than sufficient strength during construction. In more extensive laboratory tests, fully cured AAC – mortar bonds were found to have strengths up to 80psi. We tested samples with USG Moulding #1 plaster and USG Hydrocal gypsum cement. Although the average tensile strength for the Moulding #1 plaster mortar is higher (54psi) than that of Hydrocal mortar (44psi), the range of tensile strengths is also greater. Moulding #1 ranges from 25psi to 80psi, whereas Hydrocal ranges from 32psi to 71psi. The greater consistency suggests that Hydrocal is the better mortar choice for vault building, but either is a reasonable choice. We also tested the tensile strength of the AAC tiles with no bond. Their tensile strength (63psi), is on the same order of magnitude as that of either mortar bond.

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23 Material tests were carried out in collaboration with MIT Building Technology Masters candidate Wanda W. Lau, and conducted under the direction of Prof. John A. Ochsendorf, Prof. John E. Fernandez, Dr. John T. Germaine, and Stephen Rudolph.
24 Mortar tension test and dome load test proposal are attached as appendices.
25 Conducted by Wanda W. Lau with samples I prepared. Tables by Wanda W. Lau
### AAC Bond Strength Testing

**Material:** Wet Face with USG Molding #1  
**Date:** 12-13 January 2006

**Note:** Negate self-weight of the test specimen in internal moment calculations.

<table>
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<th>Dimensions (in.)</th>
<th>Bond area (in²)</th>
<th>Moment of Inertia (in⁴)</th>
<th>Total Failure load (lbs) Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Internal Moment (lbs-in.) Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Failure tensile stress (psi) Test 1</th>
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<th>Test 3</th>
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**Average tensile stress (psi):** 54

### AAC Bond Strength Testing

**Material:** Wet Face with Hydrocal  
**Date:** 12-13 January 2006

**Note:** Negate self-weight of the test specimen in internal moment calculations.

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<th>Internal Moment (lbs-in.) Test 1</th>
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<th>Failure tensile stress (psi) Test 1</th>
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**Average tensile stress (psi):** 44

### AAC Tile Strength Testing

**Material:** AAC Tile Only  
**Date:** 12-13 January 2006

**Note:** Negate self-weight of the test specimen in internal moment calculations.

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<th>Internal Moment (lbs-in.) Test 1</th>
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<th>Test 3</th>
<th>Failure tensile stress (psi) Test 1</th>
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**Average tensile stress (psi):** 63
We built a 7' diameter dome to load to collapse in order to determine both the behavior of an AAC structure under load and the failure patterns. We loaded the crown of the 1 ¼” thick dome with a concentrated load over a 24” diameter circle (~3 sf), adding weight and measuring the load and the deflection until the dome collapsed. We found that the dome was extremely stiff, deflecting less than 0.05” before yielding at a load of over 900 pounds. The characteristics of load and failure were exactly as one would expect for a typical masonry structure, indicating that solid ceramic and foamed ceramic materials perform similarly at the scale of a building.

This research demonstrates that AAC is an ideal material for structural masonry spans built in the Mediterranean tradition of timbrel vaulting, as it offers significant advantages to the designer and to the craftsman for the construction of structural masonry spans. Qualitative and quantitative tests on vaults using AAC indicate the potential for both innovative and traditional structural forms. A variety of block sizes will work with the timbrel technique and the versatility of bearing conditions and strong adhesion with plaster allow for significant creativity. The quantitative tests show that AAC is absolutely strong enough for structural spans and that it behaves in a brittle manner similar to traditional masonry.
Load vs. Displacement for AAC Dome
5 ft radius of curvature, 45 deg. angle of embrace, 1.25 in. thick
Accounting for existing surcharge at crown

Load v. displacement curves for AAC dome failure

Graph by Wanda W. Lau.
Kirby Hollow Studio
Program

Kirby Hollow Studio is a place for Ethan Murrow to create and exhibit his art work. Murrow is a contemporary artist I’ve known for many years whose work encompasses landscape and figure painting, sculpture, installation art, and video art. Currently Murrow is concentrating on large-scale pencil drawings taken from and paired with videos of bizarre and fantastic scientific explorations. Murrow describes his work:

In my newest series, *Doomed Explorers*, I design elaborately dysfunctional gear for a protagonist who dreams big yet will probably fall far. I film myself as the questionable hero and then create drawings from the video stills. Rooted in American landscape painting, these works are huge, dramatizing and idealizing location, moment and intention.27

The art is big, beautiful, and changing. Murrow desired a space that was large yet not intimidating, functional yet attractive, and configurable to the way he works and as his art evolves. Over a series of conversations we developed a program to suit his needs:

- The business/computer/clean space
- The drawing space, big and raw
- The construction/storage space for building props and storing props and art supplies
- The shooting space for having photo shoots for the drawings and films and of the final product
- The clean space for viewing, hanging, packaging art and for snoring in on a couch called Nirvana

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27 Artist’s statement, solo exhibition, Reeves Contemporary, New York, NY 2005
34  The Hydrogen Expedition, temperature assessment, graphite on paper 18"x40" 2005

35  Grain Silos, oil on canvas, 24"x72" 1999
In time this evolved into a diagram of space such that the centrally located studio is flanked on one side by the dirty workshop and on the other by the more refined gallery.

Ethan wanted plenty of access to the outdoors to be able to work outside when possible, sometimes as a necessity due to fumes from some of the chemicals he works with. He also wanted large doors to be able to move work in and out, and to be able to pack and ship his art. Each of the big rooms has at least two entrances so as not to like a feel claustrophobic dead-end.

The workshop has plenty of space to prepare, fabricate, and store props for his videos. It gives Murrow the facilities to make frames both for stretching raw canvas and for final presentation of his work. One end is directly connected to the studio, the other opens to the outside and is connected to the studio via an outside patio.

The large central studio is for drawing, painting, and film shoots. The space is adaptable while offering plenty of flat walls for work. The space needs to bridge the gap between being open and being cozy. The walls are arranged non-parallel so that Ethan can step back, sit down, and consider his work from a comfortable chair.

The office lies between the studio and the gallery. Here Ethan can work on the business of being an artist as well as edit and produce his videos. The gallery itself offers a space where Ethan’s art can be displayed and shown to clients and dealers without cleaning up the studio. Should the necessity arise to have a large exhibition or formal event, the gallery and studio can be used in concert.

The sectional diagram facilitates these three spaces via a large central span supported by occupied buttresses. The covering vault is a rampant arch to give greater height and variety to the space below.
Site

Kirby Hollow Studio is in Dorset, Vermont, in the southwest portion of the state. The studio is on former pasture-land which has since grown in and is now protected by conservation easements, surrounded by fields cultivated in hay. The building site is exempt from conservation restrictions.

The area is rife with the remnants of agriculture. The studio will be at the end of an abandoned field-road defined by windrows of old sugar maples and crumbling field-stone walls.

The studio will be built on land between the track and a lovely mountain stream. Here, rising above a small clearing, the land flattens out into a suitable building site. The main entrance of the studio faces the field-road while the primary views from the studio are northwest toward the stream.
41 View from the site to clearing above stream

42 View from stream to clearing and building site beyond
Design

The design grows out of experiments in form, structure, and space responding to Ethan’s needs. The building’s genesis is in a spiral staircase lodged at the vertex of the two intersecting walls of the studio. The curved wall defines the entrance and organizes the design. The outside of this wall slides open to reveal the main entrance covered and protected by the dome above, while on the inside the spiral stair offers a way to view the work in the studio from a variety of levels and vantage points.

The shape and orientation of the vaults underwent a number of iterations as I worked to define their relationship to the building.
Ultimately the vaults were oriented to the East to catch morning sun and remain in neutral light throughout the rest of the day. North light is let into the studio where the third vault extends to the ground. The outside shape is a smooth funicular curve of the vault from roof to ground, while the interior is a vertical wall for making art.
Kirby Hollow Studio plans and sections
Entrance to the gallery
Looking from gallery to the studio
Looking up the stairs toward the office space
Structure

My experience with timbrel vault structures and construction allowed me to design plausible vaults before checking and refining them with a graphic static structural solution. Nevertheless, the biggest challenge and greatest pleasure in designing the Kirby Hollow studio was figuring out how to configure the intersection of multiple vaults and balance their thrusts.

After most of the spatial organization was worked out, I developed a full-scale CAD model from which I could cut sections. I then evaluated the section using automated graphic statics using dead and live loads. This resulted in a revised section that more closely reflected the loads in the structure.

Symmetrical and asymmetrical loads balance within the thickness of the vault
54  Studio section prior to structural analysis

55  Final section which balances vault thrusts
Detail

The vaults of Kirby Hollow Studio are structurally designed to work in pure compression. Most of the vault thrusts are also resisted by forces in compression, either where two opposing vaults meet or where the workshop vault bears upon the ground. The exception is the dome over the entrance and the spiral staircase, where there is no opposing force to meet the thrust. Instead, the thrust is resisted by a tension band of steel strapping embedded in the AAC masonry. This strapping works in much the same way as the experimental post-tensioned beam (see figure 26), but it is much more substantial.
Cost

The roof vaults of Kirby Hollow Studio benefit from cost savings because of the use of inexpensive AAC and the larger unit size possible. The same metrics used in the analysis of the Pines Calyx apply, except that the prevailing labor rate in Vermont is $15/hr,\(^{28}\) in contrast to the £15/hr cost in England. As such, the structural shell of the vaults could be built for an estimated $15/sf.

<table>
<thead>
<tr>
<th>Material</th>
<th>Build Hours</th>
<th>Labor Cost</th>
<th>Total Cost</th>
<th>$/sf</th>
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</table>

Table 2 Cost comparison for the construction of Kirby Hollow Studio vaults

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\(^{28}\) [http://www.vtlmi.info/earn.htm](http://www.vtlmi.info/earn.htm)
CONCLUSION
Timbrel vaulting has a rich history, a fascinating construction method, and real potential to expand through the use of new materials. The completion of the Pines Calyx in St. Margaret’s Bay, England, the ongoing development of the Mapungubwe National Park visitor’s center in South Africa, and the design for Kirby Hollow Studio all demonstrate a renewed potential to create expressive architecture through the use of structural masonry spans.

AAC offers the timbrel vault technique time and material savings which translate directly to greater economy. This is a real consideration in the construction market today, especially when introducing a novel method. Building with AAC is a vast savings over traditional timbrel vaulting; further built examples will demonstrate how competitive it can be with standard industry practice. The qualities for which people choose vaulted structures, including good light, strength, longevity, clear spans, and ease of construction and modification, are often difficult to create completely using conventional construction methods.

When looking for ways to build in the 21st century, there is great value in turning to our traditions and merging them with contemporary techniques and materials. The techniques used to design and build timbrel vaults illustrate that using modern materials with traditional craft capitalizes on the significant strengths of each. These new buildings demonstrate the economic efficiency and formal viability of timbrel vaulting in contemporary architecture.


Method Statement for Second Dome at Pines Calyx
By Sarah Pennal
with contributions from James Bellamy and Michael Ramage
© 2005 Sarah Pennal, used with permission

First Layer - Soffit
Fixers
- Sarah, Paul, Royd and James

Setting out
- Check that central pole is on the center mark of the first floor slab. Make it plumb and as rigid as possible
- Make sure that the top central pole is well above springing line
- Central pole must have three horizontal braces, these will also hold up the tarpaulin
- Check ring beam for level and radius before starting, screed as necessary to level. May need a wooden bead to do this as on first dome
- Draw radius onto rebate. If the radius comes away from the back of the rebate so that the tile does not touch the back of the rebate, this area must be built up using a cement mortar which introduces the correct location of the rebate and gives a solid base from which to fix
- Check the rebate on the concrete arch
- Fix first course of tile to the back of the rebate

Formwork and cintrel
- Check central pole for plumb before attaching any of the formwork or cintrel
- Set up 4 or 5 complete formers, if space and necessity add half formers to the lower half of the dome where needed
- Fix formwork to level, and equidistant from center
- Support formwork in similar way to previous dome
- Check central pole again for plumb prior to work starting
• Fix cintrel to the leading front edge of the tile
• Check cintrel against both sets of formwork prior to fixing
• Never fix the cintrel to the concrete arch, only ever fix it to the formwork
• We have a new cintrel method for the second dome, please make yourself familiar with it prior to fixing starting
• The plywood formwork of the concrete arch will remain in place during the construction of the dome. It can be removed once the dome is complete [or before, when up to the start of the oculus]

Mortar
• Fine casting plaster
• Keep plaster dry. Store in container and only bring onto site as needed
• Buckets of plaster left on the scaffold overnight must be covered up
• Any tiles on the first layer that are not covered by 2nd layer must be covered with tarpaulin overnight

Tile
• Flolite tile [lightweight]

Fixing
• Think quality
• Stand back from your work regularly and also look along the line of tiles to check for alignment
• The dome has 3 different ways in which it can deform from its intended shape: vertical, horizontal and radial.
• When fixing a tile always ensure it is at eye level.
• Tiles are of varying thickness; so always fix to the face of the tile to the soffit rather than the extrados

• Choose your tile, as a waller would do, where possible use the concave side down
• Make sure the ‘ROBUS’ stamp is on the extrados not the soffit
• Any dirty or defect tiles must be saved to use on the two outer layers around the oculus

• Work in teams of two: one fixing, the second person supplying the materials, checking that the pointing is done as work progresses, cleaning up, cutting tiles etc.

• One fixer only to work on each working layer between the formers

• Always finish a complete ring of tiles by the end of the working day

• Avoid large waves on the soffit of the dome

• Tolerance of 15mm over the soffit of the dome

• Keep joints as tight as possible

• The first plaster of the day may take a little while to go off. It helps to make up a batch in the bucket, leave it to set so as to get some dirty plaster in your bucket to assist in speeding up the setting process.

• Plaster also takes longer to go off in humid and in wet/damp conditions

• The first course, which sits in the rebate of the ring beam, must be fixed using the cintrel

• This is followed by four courses that are built as one working layer

• From the 5th course upward, the working layers reduce to three courses in height

• From the 17th or 20th course upward [approx. 2m from the springing], the working layers reduce to two courses in height

• From the start of the oculus, the courses must be built up individually using the cintrel for each

• The number of courses built by eye should not exceed three at any time

• Always make sure that the top course of the working layer you are building is fixed using the cintrel
- Always make sure that the last course you fix in the day has been fixed using the cintrel
- Each layer to be built with a stepped leading edge; fixing one brick on each of the courses from bottom to start each layer/course from opposite sides of the concrete arch, fix the required number of courses to produce the necessary arching action between the concrete arch and the previously constructed courses
- Bring the tile out a little from the bottom bed when meeting the concrete arch to achieve the correct radius, the new cintrel method will help with getting this correct
- If big lips do occur on the front edge of the tile, these should be ground off, or plastered out, as circumstance dictates
- Lips on soffit of the dome to be kept to a minimum
- Alter all mistakes gradually over a series of tiles or courses
- Never go low

Pointing
- Remove excess gypsum when still wet during fixing = less pointing and a clearer view of where tile is placed
- Fill all holes and ensure all joints are flush pointed as soon as possible after tile is fixed i.e. when plaster still green but not if there is a risk of loosening the tile. We point as we go this time
- No gaps in the pointing. Looks poor and means the concrete of the upper layers may come through
- Fill the joints on the extrados with plaster; if possible use the plaster that has started to go off to do this
- Smear diagonal sweeps of plaster across the extrados of the courses you are fixing
- Scrape the soffit free of snots of plaster as we go

Cleaning
- This is under discussion.
Bonding
- No straight or zip joints over more than two courses
- 2 course rule: straight joints can happen over 2 courses but must be bridged on the ‘third’ course
- A stack of 2/3rds length tiles should be cut to help achieve good bonding
- Bonding should not be less than 50mm from tile edge [from either the previous course or the one being fixed]
- When fixing from the concrete arch ensure that the bond is varied, to help avoid straight joints
- Full tile used until oculus – first course of oculus full tile – 2nd 200mm tile – 3rd 4th 5th courses ½ tile – 6th course 120mm tile – 7th course full soldier – 8th course cut soldier. The oculus on the second dome is smaller than the first therefore the measurements [which are taken from the first dome] for the cuts at this point may be different
- Around oculus be aware that no tile is bridged
- As a course comes to a close cut a small amount off the length of 5 or 6 full tiles in order that they still look like full tiles and so we don’t end up with tiny cuts to close a course

Cutting tile
- Use wet saw not the grinder to cut the tiles. Always wear appropriate safety equipment

Dismantling formwork
- Shake formwork to ensure it is free of the dome soffit
- Dismantle the formwork in reverse to how fixed – from the center outwards
- Do a visual check of the dome as each formwork is dismantled

GENERAL STATEMENTS
- Do not point-load the dome at any time
- Do not pass materials over the edge of the dome; take them up the appropriate access routes
• Cover the working edge of the dome and any uncompleted layer with tarpaulin
• Put all power tools away in container
• Keep all remaining tools covered and dry
• Keep the site clean and tidy at all times
• The working day has not finished until we have reached a satisfactory stage in construction i.e. a soffit ring is complete and covered by a complete second layer or a third layer ring has been partially completed but is evenly spread over the extrados
• If in doubt about anything ask Sarah

SECOND AND THIRD LAYERS – EXTRADOS
Fixers
• Ian, Alisa and Sam
• Think neat
• The upper layers are not structural until the mortar has set
• Each layer must be loaded evenly by the layer above it during fixing
• No standing on the first layer or the second layer
• Use off-cuts from first layer when in fills needed
• When each outer layer is complete Sarah will check it and take a photographic record, do not cover any layer until this has been done
• Do not point-load the dome: always spread people and materials out around the extrados
• Run wheelbarrows of concrete around ring beam, not onto the dome

SECOND LAYER
Mortar mix
• 9 : 2 : 1 - Sharp sand : Cement : Lime
• Ensure the mix is fairly wet
• Do not let mortar dry out too quickly during curing
Tile
- Grog [heavy] – except around oculus where it changes to Flolite [light weight]

Fixing
- Check for gaps in the joints of the first [plaster] layer before fixing second layer, inform 1st layer fixers because they must fill these before you can carry on fixing
- Wet first layer before fixing second
- Lay all tiles with their concave side up so as not to trap air below the tile
- Must load the first layer evenly
- Must have first layer completely covered by second layer before the end of the day
- Do not lay cement onto an uncompleted ring or freshly fixed gypsum
- As a general rule do not stand on the 2nd layer. It is OK to do so once set but it is not good general practice
- The second layer must have set before fixing the 3rd layer
- Use Grog tiles on the 2nd layer up until the oculus.
- Use Flolite tiles for both the 2nd and 3rd layers around the oculus

Bonding
- A ring of stretcher tiles goes all the way round the edge of the dome first
- Tiles laid at 45˚. This angle will need resetting occasionally [as first dome] to do this introduce lines of stretchers over each former
- The bonding changes to soldier around the oculus
- Half bond wherever possible
THIRD LAYER
Mortar mix
• 9 : 2 : 1 - Sharp sand : Cement : Lime
• Do not let mortar dry out too quickly

Tile
• Grog [heavy] – except around oculus where it changes to Flolite [light weight]

Fixing
• Wet second layer before fixing the third layer
• Lay all tiles with their concave side up so as not to trap air below the tile
• Must load the second layer evenly
• Do not stand on 3rd layer until the mortar has set
• Use Grog tiles on 3rd layer up to the oculus
• Use Flolite tiles for both the 2nd and 3rd layers around the oculus

Bonding
• Soldier coursing. This changes around the oculus, follow bonding as shown on first dome
• Soldier courses should be laid radially i.e. pointing toward the central pole
• Half bond wherever possible
• Light screed on third layer must be keyed using a thin-set float

SCREED LAYER
Mortar mix
• See manufacturer’s instruction

Fixers
• 2 mixing : 4 on extrados
Fixing
• Must be done as one layer with no joints. Done in one hit, no tea breaks. Ensure adequate water run off where screed hits wall
• Follow directions as per additive product
• Must keep a wet edge going. When meeting an old edge ensure that it is thoroughly wetted down and then painted with the slurry prior to fixing

GENERAL STATEMENTS
• Do not point load the dome at any time
• Do not pass materials over the edge of the dome; take them up the appropriate access routes
• Cover the working edge of the dome and any uncompleted layer with tarpaulin.
• Put all power tools away in container
• Keep all remaining tools covered and dry
• Keep the site clean and tidy at all times
• The working day has not finished until we have reached a satisfactory stage in construction i.e. a soffit ring is complete and covered by a complete second layer or a third layer ring has been partially completed but is evenly spread over the extrados
• If in doubt about anything ask Sarah
Load Tests of AAC mortar bonds

This proposal outlines tests of AAC mortar bonds in tension and compression. The compression test will consist of loading two blocks of AAC that have been mortared together to test the effect of various mortars on the compressive strength of AAC assemblies. The tension test will be a four-point load test to determine the tensile capacity of various combinations of mortar with AAC.

Compression test

Geometry
The blocks in compression will be 4” cubes of AAC mortared together with gypsum plaster, 3M DP600 epoxy, and thin-set cement

Testing procedure
The load test will be carried out in the CEE testing lab, 1-034. Each AAC/Mortar combination will test three identical samples.
Loading rate: Approximately 2000 lbs/min
Measurements: Stress
Strain
Documentation: Still photography
Data for load-displacement during each test

Four-point load test

Geometry
The AAC four-point load test will use a modified version of the CEE setup for ASTM 4-point load testing, designed in conjunction with Steve Rudolph and Dr. Jack Germaine. The modification will accommodate 6” wide sample materials and allow a 6” spread between the internal loading points.

I estimate the minimum load capacity of the specimen is 10 pounds, so the test setup should weigh less than this. The maximum load I
anticipate applying in the test is 160 lb, so the test setup should be able to withstand at least twice that load.

Testing procedure
The load test will be carried out in the CEE testing lab, 1-034. I will use the same three mortar types as in the compression test, applied to 6”x12” tiles that are 1”, 2”, and 4” thick. Again, there will be three identical samples for each size.

Loading rate: Approximately 50 lbs/min
Measurements: Deflection at joint
               Load
Documentation: Still photography
               Data for load-displacement during each test
Structural Load Test of an AAC Dome

This proposal outlines a structural test to failure of a thin shell masonry dome. The goals of the test are to determine the collapse load and the failure mechanism for a masonry dome with an applied point-load at its crown.

Geometry (all text dimensions are to the intrados)
- Radius of curvature: 59.4 inches
- Span at base: 84 inches
- Rise above springing: 17.4 inches
- Angle of embrace: 45 degrees or 0.79 radians
- Thickness: 1 inch
- Material unit weight
- Tile Geometry: 4”x8”x1.25”, cut for tighter curves

Dome construction
The test dome will be built using traditional methods for timbrel vault construction, with a change in the typical material of brick or terracotta tile to AAC tile. The tiles will be laid in fast-setting gypsum plaster mortar. Structural formwork will not be used in the construction, but guides to ensure the correct curvature will be employed. A 24” diameter concrete cylinder 4” thick will be poured at the crown to provide a loading pad.

Safety
The primary concern during the load test will be the safety of personnel involved. All participants must wear appropriate safety gear, including heavy long sleeves and pants and safety glasses.

The tension ring has been designed with a safety factor of over 4 times the expected maximum tension at the base of 3400 pounds so that it...
will not yield during the loading, making sure the test will be relevant. The dome has been designed to fail at approximately 3000 pounds, so that the failure load on the structure does not exceed the capacity of the instrumentation.

All CEE testing equipment not directly involved in the test will be moved away from the testing area, and sensitive equipment will either be moved to another room temporarily or covered.

Ultimate load capacity estimates
AAC Material properties (compression, tensile, bending)
Compression: 600 psi
Tension:
Manufacturer ~120 psi
Assumed 0 psi
Expected point failure load: 1900 lbs

Testing procedure
The load test will be carried out in the CEE testing lab, 1-034. We will use two 1,200 lb tables with the load cell on an I-beam between them. The vertical reaction from the loading will be resisted by the weight of the tables and the floor of the testing lab, plus perhaps additional weight on the table to provide sufficient reaction load. The horizontal thrust of the loaded dome will be restrained by the welded steel band.

Loading rate: approximately 200 lbs / minute

Measurements:
Deflection at the crown of the dome

29 Data from the Aerated Concrete Corporation of America website http://www.accoaac.com/ACCO Prop_Load_Bearing.html: “The direct tensile strength is somewhat less than the flexural tensile strength of the material. It is estimated at about 1/5 of the compressive strength. Very limited test data is available on the direct tensile strength of AAC, and direct tension is typically not allowed in the design of unreinforced construction.”
Deflection at the surface of the dome at midpoint
Deflection at the base of the dome

Load

Documentation:
Video
Time-lapse photography every 5 seconds
Data collection from load cell and displacement measurements

Predictions
Collapse load and hinge locations and pattern

Assuming absolutely zero tensile capacity, the modified membrane theory predicts failure at 100 lbs with hinges at 8 and 22 degrees from the centerline. The membrane graphical solution predicts failure prior to 50 lbs with a hinge at 21 degrees (the other would occur at 77 degrees). The membrane analytical solution predicts failure at about 5 lbs.

If the AAC can take 50 psi tension, the membrane analytical solution jumps to 1000 psi. For 100 psi tension, the membrane analytical solution jumps further to 2100 lbs. From the modified membrane theory, P values go to 1900 and about 4000 lbs, respectively.
PRESENTATION BOARDS
Catalan vaulting and compressive form
Catalan vaulting, a medieval building technique of uncertain origin, is remarkable for its thin structural curves built without the use of supporting formwork. In the late 19th and early 20th century, hundreds of years of structural brick construction developed into new forms that had not been imagined in the pre-Industrial era.
The Pines Calyx, St. Margaret’s Bay, England

The Pines Calyx is an ecological conference center in the organic Pines Gardens, nestled in the White Cliffs of Dover. John Ochsendorf, Wanda Lau, and Michael Ramage analyzed the structure of the domes using computational graphic statics, and constructed them in collaboration with a team of Spanish and English masons using traditional Catalan vaulting techniques.
Aerated Autoclaved Concrete (AAC)

AAC is a lightweight cellular ceramic that has never been applied to vaulted construction. In addition to its low density, AAC has other advantages for vault construction, including strength appropriate to the stresses in masonry spans; a rough surface well suited to the application of mortar; and good insulating and acoustic properties.
Presentation Board: AAC constructions
Kirby Hollow Studio
December 19, 2005

Presenter: Michael Ramage (MHR)

Reviewers: Kenneth Frampton (KF)
Mario Gandelsonas (MG)
Ethan K. Murrow (EKM)

Supervisors: Fernando Domeyko (FD)
John E. Fernandez (JEF)
John A. Ochsendorf (JAO)
Thank you all for coming today. I’m Michael Ramage, and I’d like to talk to you about the work I’ve been doing over the past year toward my thesis about Catalan vaulting with new materials and some new approaches to contemporary compressive form.

In many ways this work began over two years ago when I built a small vault, loaded here with over 1200 pounds of us, out of \( \frac{1}{2} \) thick brick. Through this exploration, in which I was really just trying to teach myself the masonry method, I became fascinated with the forms, the technique, and the history.
Today I’d like to spend a few minutes talking about the background research into some of the history, into the construction process of Catalan vaulting itself, and material research here at MIT into aerated autoclaved concrete, also known as AAC. Following that, I’ll spend the second half talking about the design of an art studio using the material I’ve learned in the course of my research.

In Spain I spent some time traveling in Catalonia. Here you see a warehouse by César Martinell with funicular brick ribs and Catalan vaulted roofs.
Here at home there is a great body of work by Rafael Guastavino, a Catalan builder who brought the technique to the United States. Here the Boston Public Library, one of his many fine buildings.

Turning now to the construction, I worked with John Ochsendorf and Wanda Lau (another student here at MIT) on the structural design and analysis for two 37° roof domes for an ecological conference center in England. We did the design in the Spring and I managed the construction of it this summer.
The final result seen here, one of the domes finished, still with the scaffolding.

What’s remarkable about Catalan vaulting is that you can build these great structural spans without any supporting formwork. Here the plywood you see is a geometric guide for the curvature.
We’ll see a little bit about how this was constructed: A concrete reinforcing ring beam; (some very quick masons…) and really we begin with the first course and setting up the geometric guides at the same time to make sure this first course is absolutely perfect. Throughout this construction – this is in England, just north of Dover on the southeast coast – we were constantly asked “is this the biggest one you’ve built?” and it was all I could do not to tell them that the little one I began with was the biggest vault I had built until this one. So here you can see, after the first course, we go four courses at a time. The mortar here is plaster of Paris, it sets very rapidly and it allows the bricks to build out and fly into space. The second layer then is set in concrete – a cementitious mortar – and set at an angle so the joints never line up. In total this is three layers thick. Here we’re beginning to complete the first dome and working from the inside for the first layer and from the outside for the second and third layer. One of the remarkable things about this construction is that we had a team of English masons and we had three Spanish masons come over as instructors and lead masons for the first dome. Then the English masons did the second dome on their own. It was a really interesting collaboration. Nobody spoke the same language except masonry. Which is a very powerful language. Coming to the completion of the dome, the oculus which opens up into a – it’s a 5 foot diameter hole, but it allows in a remarkable amount of light down along the structural surface.
In addition to the traditional craft of this vault, the structural analysis was based on the traditional graphic static method which uses vectors and lines instead of numbers for calculation. We used a computational graphic static method that’s been developed here at MIT largely by Philippe Block with John Ochsendorf.

We used it also to design a staircase which was built this fall. Again, all of this is in unreinforced masonry in pure compression.
Through the success of this project we’ve had some follow-on projects. This is a visitor’s center in South Africa with the architect Peter Rich which won a competition and will be built this coming summer. And there are some housing projects in England that we hope will also use the system. So we’ve been able to demonstrate, I think, that we can go back to a traditional method and update it and use it again in the 21st century.

Turning now to the material research here at MIT, I’ve been investigating this aerated autoclaved concrete, which is concrete foam. In and of itself it’s not actually a new material – it was invented in the 1920s in Sweden, but it’s only recently been introduced to the northeast United States by a company called TruStone (which generously gave me a lot of material.) It’s so light it floats.
Not only is it light, but it’s also very workable. It’s produced in these large 24” blocks, and easily cut on a band saw into tiles, and then those tiles are a perfect material for vaulting.

Because of their lightness they allow a certain exploration and variation in form that can’t be achieved with heavy bricks assembled without formwork and with plaster mortar.
Another example: this arch which spans about four feet is four inches wide and two inches thick and it easily supports over 200 pounds.

One other aspect of the work we did here at MIT is to try to understand how the aerated autoclaved concrete performs as compared to typical masonry, so we built a small 7 foot diameter dome and did a load test.

[Load test movie] We loaded it from the top. We very quickly added about 1000 pounds. The dome stood for quite a while, and eventually we got our results.
Indeed, the load versus displacement for the material is very similar to what we would expect for masonry. This load – the concentrated load – of 24” at the crown of the dome is unfavorable for the dome. It would be most comfortable under a uniform load. But we wanted to try it under a load that was unfavorable to see how it would break. We also had a limit to our testing equipment, so we had to have a smallish load so we could break it. At 1,000 pounds this dome, which was only an inch and a quarter thick, collapsed.

Turning now to the design project, I’ve been working with an artist, Ethan Murrow, who’s a member of the jury today, to design an art studio in rural Vermont. Here you see one of the views from the studio, and one of Ethan’s recent large drawings.
In the time that I’ve know Ethan his work has evolved from large landscape paintings, (this one is 4’ by 5’) to installations, to sculpture.

And now to drawings taken from video stills of absurd explorations of concocted scientific experiments. These become fantastic line drawings that are larger than life. In talking with Ethan, and seeing his work change over time, it became clear that just any studio wouldn’t suffice, because the space needs to be able to respond to Ethan as he changes his work. He needed large space, plenty of walls for drawing, but also areas that could be used for photo shoots or video installations or sculpture.
So we came up with a main studio that’s flanked on the North by a workshop and on the South by a gallery. Because of the location in rural Vermont, we wanted to have the opportunity that dealers or clients could come and Ethan wouldn’t always have to clean up the studio. The gallery could serve that purpose, and then for a major show the studio and gallery could work together as one exhibition space.

In order to accommodate this large, changeable space, there’s the main structural vault of the large central studio buttressed on either side by the workshop and the gallery.
The site is in Dorset, Vermont, in southwestern Vermont, on land that has been given over largely to conservation. The building site, allowed through the conservation easements, is here, nestled between an abandoned field road and a stream in the forest, flanked on either side by fields.
The approach to the site is through one of these field roads,

and the building itself will be in a forest of young birches and old-growth sugar maples.
Here we’re looking, on the top, North up into the site, with the building located in this area behind the clearing. And here looking from behind the building down onto the clearing.

I’d like to turn now to the design itself. Largely a single floor plan with a double-height studio. The space between the gallery and the studio is two floors to allow for office work and mechanicals and that sort of stuff. The gallery is also a double-height vault, the studio is a rampant vault which comes down into the workshop, which has the possibility for an inhabited roof coming up from the ground here.
One would be invited into the building itself through the split entrance under the wall of the dome.

You’d come into the gallery under the two-story level either walking into the gallery or down the stairs towards the studio.
Looking from the studio into the gallery to the north lights and some of the exhibition space.

A view looking back towards the walls for drawing. Again, these vaults open this way to the East and in this direction to the North.
Here looking up the spiral stairs and back to the exhibition space of the studio and up into the office, which has a doorway and some windows through to the gallery.

At a certain point in the project, after having developed the space, I came to a point where I needed to understand the structure as well, so with this sectional model, I returned to the graphic statics.
[Cabri movie] You can see the way that I’ve allowed this to work – this is the original structure, and by changing the forces in the vaults themselves I’ve tried to get a close match with the section as designed, but I actually ended up with a much more favorable form for the vaults themselves. What this resulted in is these blue lines, the lines of thrust from the vaults themselves, and very clearly there was a need here for the form to respond to the forces.

So the final section of the design: the vaults come up much higher and then there is the supporting buttress at an angle.
Finally, getting towards some of the realities of construction. Most of this building is built in compression, but there are a few parts where the thrust needs to be taken in tension. Because the aerated autoclaved concrete is so workable – you can basically use woodworking tools with it – I’ve developed a system – which I used here in this post-tensioned beam – whereby routing out a channel you can use industrial strapping to take the tension – that’s what I’ve used here. The vaults of the spiral staircase taken in tension here, as well as the thrust of the dome over the entrance.

Looking at the construction cost for this, if we were to build this using the tiles that we built the domes in England with, which are very thin brick but they are hand made (they are about $3 a tile), this building would have come out on the order of $34/sf or $157,000 for the structural vaults themselves. Another option would be to use split brick, which is the largest brick available in the United States which is much cheaper – these are a dollar each – but they are much smaller too, so it takes a lot longer, and that’s $34/sf also. Using AAC, I can use a much larger brick, so it’s much faster, and these are a lot cheaper – these are about $0.53/sf. So in total the structural vaults are $15/sf using this system. Which...KF: Are they also then bonded in Catalan formation? MR: Yes – these are bonded using plaster in the Catalan formation. KF: In three layers? MR: Yes in three layers. MG: But they are thicker. MR: They can be cut to whatever thickness.
In conclusion, I hope I’ve been able to create a space for a young artist unlike any other in Vermont. I think I’ve been able to demonstrate that the economic efficiency and formal variety and viability of Catalan vaulting, not only in this project but also through the project in England and South Africa. Finally, I’ve been able to show that in looking for ways to build in the 21st century, there is a great value in turning to our traditions and merging new techniques – looking at old traditions with modern materials.

With that I’d like to thank the many people that have contributed to this project and turn to the discussion, and to thank you all for your attention.
KF: To start a conversation...It’s an amazing project. Astonishing work.

That whole presentation is very convincing from the whole technical and imaginative use of new material and so on.

The one thing that occurs to me is this question of – well. You showed at the beginning this amazing space by César Martinell, a space I’ve never seen, and somehow this makes me think of other Catalans, for example, Miralles, for a start.

And, and this question of geometry on one side and the capacity, and the importance of geometry and the coherence of geometry in order to achieve this structural flow in the material, and you, at certain points interrupt the structural flow in the material. And then you use...as you pointed out these tension members to receive the thrust. But if you go back to the program, and describe the program, the office, the through part and division, you suddenly think well after all, most of this could be achieved through freestanding screen walls and a freestanding prism – that would contain the offices – and the whole lot could be covered by a dome.

Or a propped dome without the use of verticals. I mean the opposing use of verticals. So that would be my main reservation.

The two things together: this question of the choice of geometry, the role of geometry in modulating the formal idea in relation to the structural flow. People who impress me a lot are Foreign Office Architects, because they use...that little book – the little green book -- and this idea of phylogenesis. This notion of theirs, a very geometry based; according to the program, according to the subject.

Geometry has its own internal coherence, and that drives the, at some point drives the concept in relation to structure. The flow of gravity through the structure. I think my main reservation would be that.
MG: Well I have some questions, and I would like to look at this from a different point of view. I also was really impressed with the presentation. It was, I thought what was very interesting was your direct involvement with the construction, the way you placed yourself in the process of creating these vaults. And I was interested in the fact that the – well that’s what the Catalan vault is about – it’s about construction. It’s about… it’s not about drawing and then building. And the question for me comes when the project enters the story and where you start by drawing, and not building.

I thought it was very interesting the point where you needed to modify the drawing. Change the drawing. That’s the point where you brought those two, we could say these two worlds together. Now I think that this thesis, if there is a thesis, would be located there, in a way, in the intersection, or the overlap, or the contradictions, or perhaps even the impossibility of bring those two worlds together. And I think when Kenneth mentioned this large vault, something independent of that vault in a way accommodating the programs. He is referring to the same question in a different way. That would be one solution which is to split these two worlds. And if you attempt to bring them together I think that I would have loved to have seen more time spent in theorizing and in achieving the meeting of those two worlds.

In the same way that is what I was interested in the first part of the description was this very long process where you learned about the technique where you changed the technique and brought it, that was interesting. I was interested. Something you said about bringing back, about bringing perhaps to the present a technique one that obviously is not a contemporary technique.

But then I would say the second part of the presentation, when you bring now this new, what you achieved, transformation of that old technique together with the architecture of the plan and section and the program, I wish there would have been more, you would have gone slower at that point.
Because obviously what you’ve shown first are either large structures that are one shape that is very very large or the accretion of cells like in that other project. That whole thing. The question for me is how do you go from that to this other situation where you are now in a way forcing the Catalan vault into a world that’s not exactly wants to be. You see what I’m saying? So I find that interesting; forcing it, or trying to bring it into an unnatural situation.

MHR: I think both of your comments are very relevant and very interesting, and related, as you say. The geometric aspect of it, I think, came largely in plan, thinking with Ethan about how the spaces should work. The original generator of the geometry came from looking at the site as a triangular area that was really organized by the spiral staircase at one end. And from that grew the organization of the space. You’re absolutely right about the accretion of uniform vaults or the large scale covering by one vault.

One of the things that I’ve found very exciting in this is to imagine how many vaults can work together. This point where I went from the design in the middle, which is near John [mid-term model].

Basically the point at which I went from that [mid-term model] to this [final model] was with the structure. You can handle these if you want. Essentially it’s what happened with this staircase as well, which by the very fact of code had to have a landing in the middle of it. And playing with the form of it. We know where the stairs, the landing had to be, and what was the form of it the supporting all that and playing with that through this process of form finding and going back and forth. I think that your comment about the timing is fair, because it would be wonderful to go back and forth a few times.

MG: For instance, my problem is if you want to locate it here…is here [intersection of gallery and studio] and there [join of studio and workshop]. I would have loved to see a full project developed starting from here [intersection] and following the logic of this piece.
I’m sure you could have developed that. And then another project where you take the logic of this piece and you extend it back here and there. And finally when you go from this shape to this volume, this orthogonal volume.

The question in terms of geometry in the traditional vault you are working always with perfect shapes. Round or, let’s say parallel alignment. When you get into triangular shapes or shapes that are not pure the vaults change. In that sense I’m saying I would have liked to see the full development of every one of those different alternatives and then bring them together. In that sense I thought of going slow. And perhaps more methodical way. There is something of a collage in the project in the way you bring those pieces together. My question would be: where do you slice? It’s like when you put together a quilt, where do you slice the individual patterns? Are the squares small, or big? Obviously there is a correspondence between your program diagram and what’s happening here.

FD: I think it could be good for Michael to explain the issues that you were dealing with in the design because there is the question of the landscape; how this building accommodate to the landscape. What is the relationship between the building and the outside to the landscape, the outside. You haven’t explained very much, because that gives you the sense of the alternative geometry. What is the light about, because for example the organization of the light is toward the South. So there are issues here that are has not been enough clarified enough in the process of the presentation so maybe you can explain to us the relationship of the studio toward the outside. The light penetration, the connection between the workshop and the other entrance form. The interest of this collision of geometries and forms and tectonic forms is the how they match together. They don’t match. It’s in that friction that is really operate the innovation of the way to perceive and understand these vaults as originate the forms not follow the precedents examples but become a renovation of the process of design. A type which has different character, different qualities, this play of light and movement.
MG: I wonder why Michael is not responding to my question by bringing that model [small vaults]. This is basically what I was asking you to do. I was waiting for you to tell me why you didn’t go that way.

MHR: Well here we go. This...

MG: Because what I also like is the fact that we have all these alternatives and explorations. I find this extremely interesting. I never thought of the possibility using the Catalan vault to do this.

MHR: I too found this very interesting. And essentially, I can confess to having designed from this end that way. I probably don’t need to explain that. So the public face of the building became the place where I started, and having worked this way, essentially the private space where Ethan has access to the outside, to the stream, to the forest is in this, unfinished. What worked here, for me, was the large vaults spanning the space with a different entrance, but what didn’t work for me, or what I couldn’t reconcile, was, how do you, (and it’s always the problem in the vaults I’ve worked with) how do you end them? One way is easy because that’s where they want to go, that’s where the forces go, but then this side, what do you? You can’t just leave it open. Or maybe you could...

KF: You could.

MHR: That didn’t…But this is a western facing wall.

MG: Two things: one is how do they meet the ground, the other is how you enter these spaces.

MHR: It was in this factory, for example, with the multiple aggregate roofs. It’s beautiful in the middle but at the edge it’s just cut. And that was something that I was trying to work around.
KF: But you have a cylinder to uphold the rim. Are you talking about the ecological [Pines Calyx]

MHR: This has a cylinder. This dome ends quite well.

KF: Yes, It ends in a ring.

MHR: This factory is just cut. Right at the edge. So in the middle it’s absolutely spectacular. But at the edge it just ends. Which is fine...

KF: But you have projects by Freyssinet, for example, which end like those. They don’t cut. Do you know these Freyssinet shell vaults? Factories?

MHR: No, I don’t.

KF: See this is something I really think is which is that when you start to enter into this you have to go back fully to the culture of structure in the 19th and 20th century. You can’t just seem that all these people Freyssinet doesn’t exist, this one doesn’t exist. This is crazy. People have thought about the problem, you know. And so this one-off factory in where ever it is, Catalonia I suppose, is not, can’t be taken as exemplary of the issue, because other people have handled the issue with much greater engineering elegance than that. So you know, you need to look with very wide eyes at what people have done because there is really a lot of material there. You don’t have to – you know it’s a terrific, very exciting project, but then when you enter you should enter fully into that culture. Do you know what I mean?

MG: And to complement what Kenneth is saying, I think it’s also like Freyssinet, or we can think of a number of engineers, this is what can see what we think of as a thesis in every project. And then I’m looking at that other model [bent wood] and I’m thinking that’s probably not something I would be interested in exploring but that
could have been one way of looking at this project where you have those two boxes with vaults spanning in between.

It’s like you know there is one idea the second idea and the third idea, and I think that you are giving yourself too many things to work with. I’m looking also at that other model, [chicken wire] which in a way that would be an answer to my question because this in a way is dealing in a different way of dealing with one line of research and in this case ending it on a wall and splitting it in the center. And I think that’s plenty to work with. You see what I’m saying? I think there are too many moves, one idea would have been enough. Because they are all very rich.

EKM: Can I just add…I’m just obviously naive from an architectural standpoint but I think that one of the things that I talked with Michael about was obviously the flexibility of the space, which I think are some of the things you all are discussing. But the other thing I asked for as the pseudo-client was to have a real mixture of spaces that were intimate, and closed, and spaces that were open. And one thing I wonder about if they were larger open spaces would be how an artist would inhabit that space. Because when I think about these grand arched spaces I have a concern about how I would personally inhabit them in a smaller way. I don’t know if that makes sense. But that would be my question about a switch in design from some of these spaces which I appreciate for their mixture of size from a contained small office to a larger opening. I’m not saying that couldn’t exist in the spaces that you’re discussing but I just wonder about how that would work in a larger grander arch.

MG: Well, that goes back to my first comment about these three different zones and the point where they split, and in that sense I think the investigation in my view could have been focused on those two difficult sections. How you cut and move them. Because this is obviously A, B, C, which is a difficult proposition for an architectural composition. Usually you don’t do that.
KF: I think the other interesting thing is this question of the dome, because if we take a Bucky Fuller dome, very difficult to get in. Always difficult to get in. And of course this is not this pure, almost neo-platonic dome, as a Bucky Fuller dome is, but so it has more variation because of the Catalan, the more plastic view of vaults and shells and structures, not so platonic.

But what makes me think of the, which is also connected. I’m obsessed with a particular hypothetical dialogue between the roof work and the earthwork and I think that you do, I mean there is earth work here because there’s this change in section but there’s not too good a connection between the thinking of the earthwork in section and the idea about the site. Although you do talk about the site and we see this computer photo montage. You still don’t have…for instance there is no path in this thing. And this question of how you enter building anyway, whatever buildings, how you arrive at these buildings, in terms of topography and the earth work is a key factor. Because there’s a point at which you penetrate, finally, into the structure. But the preparation for that penetration is the earthwork and it continues then inside the structure.

Why of course I’m a bit too over impressed with Miralles but, the archery of Miralles (1992) is also very beautiful from this point of view because the shells, which are not really Catalan, but are folded concrete slabs with hollow pot pieces inside to reduce the weight are propped by tubular pieces of steel. And this again brings me back to a cultural issue which is that this Catalan Movement was based of course on an Arab culture finally, the Roussillon vault, or the Catalan vault comes from Arabs but in the 19th century with the Gaudi etcetera etcetera. They are fed by Viollet le Duc which involves the hybrid of the metal and the shells structure and that’s what Miralles is using in the archery, and then this point of entry in other words, this point of rupture can be perhaps..

Possibility: of articulating it through a transition from one material to another material in relation also to the earthwork. He turns his roof
work into an earthwork almost in that archery building. Where he plays ambiguously ‘cause whether the roof is or is not the ground. It’s another ground in a way. You talked about walking on the roof also…You know it’s a wonderful project, but I think this question of looking for the cultural games is the next move to make. The other thing is just a footnote: In Columbia there is a Guastavino chapel. In that chapel, in a side room there is a staircase, of course it’s pre-code a helical staircase, so in fact it’s a Catalan helical beam going between one floor and the next. There is no infill. It stands free. It’s an amazing structure.

MHR: and the only reason for the infill here is the code.

KF: otherwise you could do a continuous helix. It would be the same principle.

JEF: One thing I wanted to say about the work here (again I’m one of the advisors so I’ll be very quick) but one thing that I do think is a potential that you’ve revealed and I’m only really seeing it now is that in all of your studies and in the final design the piece of the structure that is, I won’t say neglected, is labeled as supportive, is where the vault comes down and bears somewhere. Like here in that little study it’s just a background cinderblock wall. Here it’s just a plate of – maybe that’s steel.

And in your project it also gets translated into this somewhat sculpted earth and I think it’s interesting this question between the geometry of the vault and the wall because I want the vault when it comes down, it needs to the thrust line needs to travel, the earth could come up and bring that vertical and also bring that thrust line down, but that requires sculpting and really paying attention to that supportive…

KF: Viollet le Duc answers that by tie rods.
JEF: Sometimes I think the structural member is overly obsessed about, where the real, then the next step is at the joint, is at the connection between where it's maybe one material and another, but maybe it's one system and another. That also gives you the opportunity between the earth and the roof between the entry and the occupation of the space. I think that's a good place to look next.

KF: Another comment...something I would like to add. You know, dome anyway it's a cultural issue. Dome you know is essentially the Dome of Heaven you know. Can really think of the thing as having a dome that emits natural light, and within that is the heaven so like the earthwork. You can then put elements that are more intimate lit from above. You could change to wood for example and move it around.

FD: As happen in this room for example. Big space where contain now with other partitions. So the partitions come up from the ground. One thing that is interesting in this process has been the invention, the other possibility toward the limits. It's a limitation in the process of making, and in the material and in the way to work. At the same time that provoke a highly inventive position.

For example we have been talking here is the way that wall on the other side introduce the light and the landscape. You turn that for there is a series of moments here of invention which I think is interesting we can take the other aspect of this forms, no? How they become the wall now become part of the vaults. So there is some richness in this process in that direction. How, in the way in engage the ground and well, I agree with the other comments as well from the point of the friction between one structure and the next. We talk about that seen from here as more one being three. So I think there is something was very interesting in the process of making these sort of ruins. Appear as the rest of things.

This dialogue between the pieces, the parts of something which have become together by a common experience of light, for example, or a
common experience of ground. So the way to unify the parts in one, is not only have to be one vault, but could be as Hagia Sophia, for example, it can be several different configurations and it’s connected to ground and to light. So in fact the issue of the really making one is quite deeper understanding. One thing could be this is formally one or two, the two as this one become one. The other thing is they could be unified in the way that they catch the light.

Through different parts you realize as one or is the ground who make that, or is the roof who become ground, or is the...well issue is less tangible which can realize the unity of the building at another level than just the reconfiguration of something that is one dome. In that sense there is an interesting investigation challenge that really go to the edges in many way but achieve to the understanding is recognizing there is something here altogether is one. Which is not the one of one but is the one made by many and that is part that I found very attractive in the project.

KF: The other thing that interests me is that I noticed on the English dome you finally have cement over the whole thing, and you would do the same here. You would put cement over the whole thing.

MHR: So one would only see the masonry from the inside. The outside...

JAO: I was going to raise that issue because the models lead us to believe that we are looking at the AAC palace, right, and you see the inside and outside this white, lightweight material. But in fact the question of what the other materials are to waterproof from the outside, I think it actually changes our impression of the project quite a lot. I’m not asking you to cover these with cedar shingles but the question is: what are the other materials in the project?

MG: what’s so interesting about this question is what is the material of this wall in relationship to the vault as opposed to this wall which is continuous with the vault. So I think that there is an interesting
possibility of blurring the difference between what’s roof or what’s wall or not. And then comes also the question of bringing those two walls together, this wall with that wall. You see, with that, I think the materiality is what would reveal the questions and the problems.

KF: But you know in that case, though the interesting thing to cover this would be with tiles. Ceramic tiles which are self cleansing and could also be used expressively as well, not necessarily all one color, or... Take it easy! But I mean

MG: I personally would go with a first coat and then put the tiles on top.
KF: Yes, you still have your coat.
MG: Ok, no...

KF: You have to do your cement. But then you put on your tiles otherwise this concrete is going to be Hell. It’ll probably crack. I don’t know what the English are going to do.

MHR: The English are going to cover that with 20 cm of soil. So this becomes an earthen roof.

KF: Which you can also do here, right?

MG: Except here, or there. That also brings a big question because there are materials that cannot be used on the horizontal.

MHR: One aspect I explored was to try to use slate shingles very common to the area as a material. Only works on the vertical wall, doesn’t work on the double curve.

KF: And common slate is antithetical to not only the double curve but to the character of the material. Shingles are sheet tradition. It’s not the same. Tile inherently has a stronger affinity to the vault. What I think is amazing is what Guastavino does. The way the geometry is worked out in the inside of the vaults so that when they finish the
system at the point of bearing there’s no…the seams are correct. That’s amazing. That’s of course more difficult to do, also another issue, with larger pieces. Makes me wonder. I suppose the Catalans modified the size of the pieces as they came down to the bifurcating.

MHR: They did, absolutely. Even in this dome as we turned up into the oculus we had to cut the tiles.

KF: But they weren’t shaped?
MHR: They weren’t shaped. They’re still…they change in size.
KF: You could cut these, depending on the need.
MHR: Yes you could.

KF: But then when you cut you risk losing the sandwich structural bond connection, won’t you. You risk coinciding joints. It’s brilliant what you’ve showed. It’s an object lesson on the way in which you do the three layers. In this way there’s no way in which the joints will coincide. They’re always counter. When you cut, there’s more of a risk of a coincidence, isn’t there?

MHR: There is, but it’s the cut on the first surface. The second surface needs much less cutting because you don’t see it and you really fill it in with a tremendous amount of concrete. It becomes a concrete in which the aggregate is a tile. And you fill up the…

JAO: We should try to finish up…maybe last comments if there are any.

MHR: As we finish, I’d like to thank you all, but I also want to get back to the cultural question, not just in terms of the history and where the vaults are, but also in terms of the building and its location. Certainly one of the things Ethan and I have talked about, is when you are in rural Vermont but Ethan’s audience is certainly in L.A. and New York and Boston. And how do you negotiate between the site of production in Vermont and the site of presentation in NY and try and create a space that can do a little bit of both?
KF: In that sense Vermont is slightly arbitrary choice, isn’t it? Why Vermont?
MHR: Specific choice for Ethan. It is a real issue. The land is…
KF: So it’s a real issue.

EKM: Is anything lost or gained in switching to the new material in terms of the aesthetic appeal, the porous quality. Is there a change there? Or are they comparable in color and texture?

MHR: I think a lot of things are gained in terms of the constructive nature, in terms of acoustics – depending what you want – but this is a fairly dead acoustic material because of its porosity. The domes have a ring to them. What’s lost is the possibility for variation in the material itself. These bricks were absolutely wonderful to work with because every one was different. And it creates something that’s magical.

These are going to be largely all the same and the magic will be in the craft of construction. But no longer so much in the material. It’s an excellent question and something to be aware of.

EKM: So highlighting the craft might become even more important.

KF: But you pay for it. Cost. You could then argue in terms of finishing the outside the savings on the basic shell allows you to finish the outside at a higher level. And there I think there’s a question of an interesting issue in terms of the idea of Vermont linking to a kind of network that is more transcontinental etcetera etcetera. The question of the color of this thing could be used to speak to the other worlds and not be so tied to harmonizing with the culture of Vermont. At any rate it’s not part of the building culture of Vermont in any case!

MHR: True enough. Well thank you all very much.
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