Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

The "Lookout" sculpture: Design and construction of freeform reinforced brick vaulting

Lara DAVIS*, Rebecca BUNTROCK[a], Martin PURYEAR[b], Rob HORTON[b], John OCHSENDORF[c]

*Limaçon Design
1 Cedar Hill Rd., Gaylordsville, CT, 06755 USA
lara.earth@gmail.com

[a] Silman
[b] Martin Puryear Studio
[c] Massachusetts Institute of Technology

Abstract

This paper describes the structural design and construction of 'Lookout,' a 6-meter-high brick sculpture by the artist Martin Puryear commissioned by Storm King Art Center in New York, USA (2023). Puryear's artistic vision, a shell form with complex double curvature, was first realized in an exquisitely carved 1:24 scale wooden maquette. The brick sculpture has the shape of an arch which seamlessly evolves into a freeform dome through a series of inclined masonry segments. The realization of the sculpture involved numerous innovations in construction technique. It was built with the Nubian vaulting technique, employing double-wythe structural brick and a reinforced structural cage cast in a concrete matrix. This reinforced shell made use of minimal formwork, utilizing the stainless-steel reinforcement cage as a constructive guidework to control brick laying. The shell is punctured by ninety fiber-reinforced cement tubes which provide views into the surrounding landscape and also function as shear ties between the inner and outer shells of brick. Equilibrium approaches were used to assess the global stability of the vaulted brick form, estimating the material stresses at the base. Additional finite element analysis was employed to refine the design of the steel cage, and shear analysis was undertaken for the tying capacity of the tubes. This paper will also describe the materials, methods and sequence of the construction, including the use of materials inspired by the rich history of masonry in the Hudson Valley, New York.

Keywords: freeform vault construction, reinforced masonry shell, double curvature, Nubian vaulting, minimal formwork, shear ties, brick, natural cement.

1. Introduction

This paper describes the structural design and construction of 'Lookout,' a 6-meter-high brick sculpture by the artist Martin Puryear that was commissioned by Storm King Art Center in New York, USA and completed in September 2023 [1].

Puryear's artistic vision, a shell form with complex double curvature, was first realized in an exquisitely carved 1:24 scale carved wooden maquette. Known for his deep reverence of craftsmanship [2], Puryear was inspired by his experiences of the Nubian vaulting technique in Mali as well as meeting the Egyptian architect Hassan Fathy in New Mexico [3]. He further discovered the "sinuous possibilities of brick masonry" in Guastavino vaulting [4] and the brick "bottle kilns" built in the U.K. [5]. The sculpture has the form of an arched opening that seamlessly evolves into a freeform dome through a series of inclined masonry segments. The shell is punctured by ninety tubular apertures – all sighted to a single point on the interior – through which the viewer sees vignettes of the surrounding landscape.

The realization of this sculpture has involved numerous innovations. The construction was conceived as an adaptation of the Nubian vaulting technique, employing double-wythe structural brick and a reinforced structural cage at the centerline of the vault cast in a concrete matrix [6]. This reinforced shell made use of minimal formwork, utilizing the stainless-steel reinforcement cage as a constructive guidework to control brick laying. Ninety fiber-reinforced cement tubes functioned as shear ties, mechanically tying together the inner and outer shells of brick. Further, a unique blend of natural cements was developed to lay brick free-spanning with no formwork, with longevity for an outdoor sculpture in a cold climate.

Equilibrium approaches were used to assess the global stability of the vaulted brick form, estimating the material stresses at the base. Additional finite element analysis was employed to refine the design of the steel cage. Shear analysis was undertaken for the tying capacity of the tubes.

This paper also describes the materials, methods and sequence of the construction, including the use of materials inspired by the rich history of brickmaking and early cement development in the Hudson Valley region of New York.

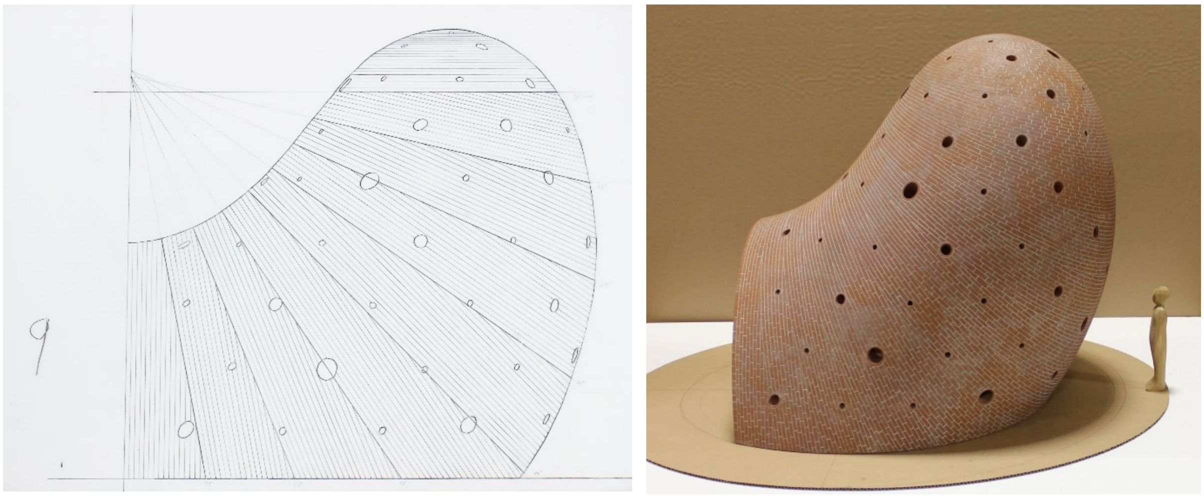

Figure 1: a. Hand drawn side elevation and; b. Scaled model of "Lookout". [Martin Puryear Studio]

2. Constructability

2.1. Proof of concept

In September of 2022, Martin Puryear Studio built a 1/2 scale mockup, approximately 3 m (10 ft) across and in height. The principal aim was a "proof of concept" of the constructive techniques, materials and technical details. While the adaptation of the Nubian vaulting technique was logical for the form, the construction posed five daunting constructive challenges:

1) Nubian vault construction without formwork requires a sticky mud mortar [7][8]. The design team needed to identify a contemporary mortar with the fast-setting, adhesive properties of clay [9] as well as longevity needed for a permanent outdoor sculpture in the freeze-thaw climate of Storm King.

2) Nubian vaulting makes use of its leaning courses to ensure the stability of the compression shell at each stage of construction [10][11]. But the complex curvature of the Puryear sculpture, with a rather severe overhang of masonry on the back side of the structure, would introduce tensile forces in some regions.

3) The reinforced masonry shell was built with double-wythe structural brick and a structural steel cage cast in a concrete matrix. The steel cage needed to be designed for a complex shape

and bent to a high degree of accuracy, such that the cage could be used as a geometric guidework for bricklaying.

4) For this structural system to work, the inner and outer shells had to function together and had to prevent delamination over time. The brick wythes needed to be tied together to insure a cohesive masonry system.

5) Finally, the masons would need to lay brick to exact geometries in three-dimensional, double curvature.

To answer these challenges, the core team drew upon the deep history of construction innovation in the region of the Hudson Valley, New York.

Brick: The New York region and Hudson Valley is famous for its historic brickyards [12] and for its craft in brick masonry [13]. While the last manufacturing plant Powell & Minnock closed in 2001, Puryear's instinct to build one of his last major public commissions in brick was inspired by the legacy of this material in the region. A custom brick with a special clay composition was produced by the Taylor Clay Company, and the construction crew included local traditional bricklayers.

Mortar: The Hudson Valley is home to the famous "Rosendale cement," a pre-Portland era natural cement with hydraulic properties that has been used in the construction of historic structures such as the Brooklyn bridge [14]. A unique blend of natural cements was specially formulated for a rapid-set which was needed to lay brick free-spanning with no formwork.

Tubes and tying: The constructability with classic brick ties proved in the mockup construction to be a real technical challenge. However, the traditional use of multi-wythe masonry has always made use of mechanical ties through the masonry bond pattern (eg. a "header" course in the masonry). Testing in the mockup was critical to convince the project team that the ninety fiber-reinforced cement tubes could function as shear ties between the inner and outer shells of brick.

Steel: While the early iterations of the 30x30 cm (12x12 in) grid steel cage were clunky and difficult to wrap smoothly around the form, the mockup construction solidified a stream-lined approach to its design. This allowed the stainless-steel reinforcement cage to be used as a constructive guidework to control brick laying. It was also designed as a 3-dimensional drawing, to assist in controlling the construction detailing and sequencing.

2.2. Methods and construction sequence

For the full scale construction, the methods and sequence of the construction proceeded as follows: After the completion of the foundations, a CNC cut formwork system was built in situ to support the weight of the arch until it could bear its own load (Figure 2). An additional guidework system was constructed to control the bending of the stainless steel until the welding stiffened the cage. Additional steel rebar elements were added to aid in the masonry construction: steel representing the dividing lines between sections and steel rings which controlled the position of the ninety fiber-reinforced cement tubes.

For the masonry construction, the inner wythe of brick was first laid with the natural cement mortar directly on the arch formwork for the first three segments of the shell. The final pieces of steel were welded in place, then the arch face was built and the outer wythe was progressively laid with regular, small concrete castings into the core. When segment three was nearly complete, the arch formwork was carefully dropped and removed, and all steel guidework was removed. From segment four onwards, all brick was laid "free-spanning" with no formwork. Only a 30.5 cm (12 inch) wooden ruler was used to register the surface of the brick against the position of the steel cage. The inclination of each brick had to be carefully controlled. Each brick around the tubes had to be carved into cradles with a grinder. The tubes were hung with a special harness system and sighted to the viewing point at the center of the structure. The brick cutting for the dome began as early as segment five and culminated in a unique, freeform elliptical dome.

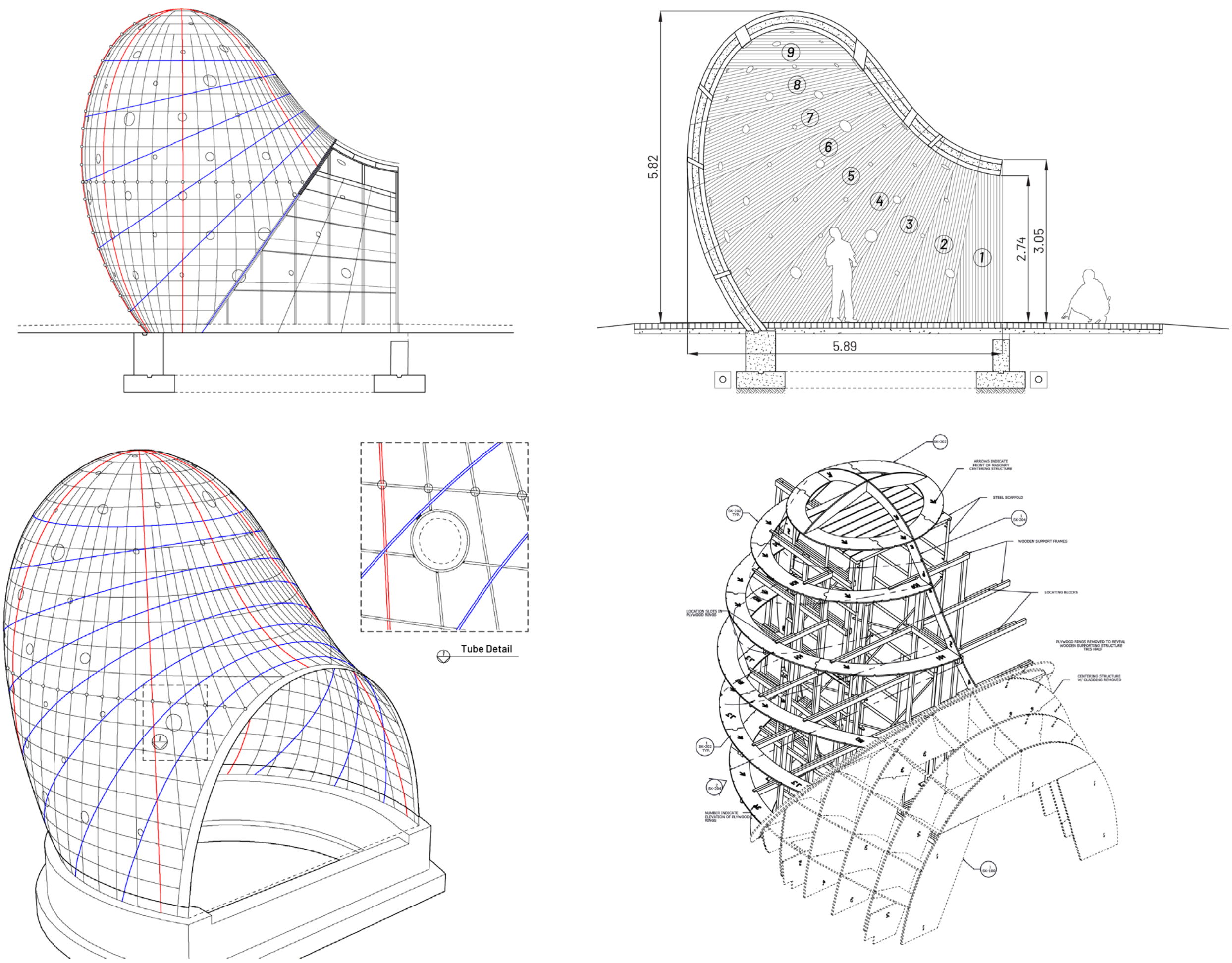

Figure 2: a. Cross section of guidework; b. Cross section of masonry showing the nine segments; c. Stainless steel reinforcement; d. Wooden formwork. [Lara Davis and KC Fabrications]

3. Structural design

The challenges which arose from the sculpture's shape and geometry, the design of the cage, and the mechanical tying of the masonry are all addressed in the structural design. This included three analytical approaches: a global stability analysis of the shell, Finite Element Analysis to refine the design of the steel cage, and shear analysis to assess the tying capacity of the tubes.

3.1. Global stability analysis

The freeform vault geometry can be roughly broken into three segments corresponding to the mode of construction (Figure 2b & Figure 3a): 1) An arch (masonry segments 1 to 3, built over a full formwork); 2) a free-spanning vault (masonry segments 4 to 6, built in a method similar to Nubian vaulting, with no formwork); and 3) a self-supporting dome (masonry segments 7 to 9, similarly built with minimal formwork).

The first assessment considered the global stability of the vaulted brick form and estimated the material stresses at the base. First, the loads were simplified according to the construction principles of the sculpture. The global I-value was assessed at the base of the structure, treating it as section of a beam. Then a stress analysis was performed at the base of the structure, computing bending stresses combined with axial stresses. Finally, lateral loads were assessed for an equivalent static earthquake load of 0.15g, estimating the total stress at the base of the sculpture due to this loading.

3.1.1. Dead load only

Based on the three-dimensional Rhino model, the sculpture has the following properties:

Table 1: Overall data.

Centerline surface area	83.9 m^2 (903 ft^2)
Thickness of shell	30.5 cm (12 in)
Width at base	4.8 m (187.9 in)
Density of masonry	2,243 kg/m^3 (140 lbs/ft^3)
Total weight	551.6 kN (124 kips)

The centroid of the horseshoe-shaped beam section at the base of the sculpture was determined (Local x in Figure 3b). Based on an approximation of the base as 20 rectilinear sections, the centroid of the horseshoe was computed as approximately 2.9 m (115 in) from the opening. This meant that the center of gravity of the overall sculpture (Global x in Figure 3b) fell within about 0.35 m (14 in) of the center of resistance of the horseshoe section.

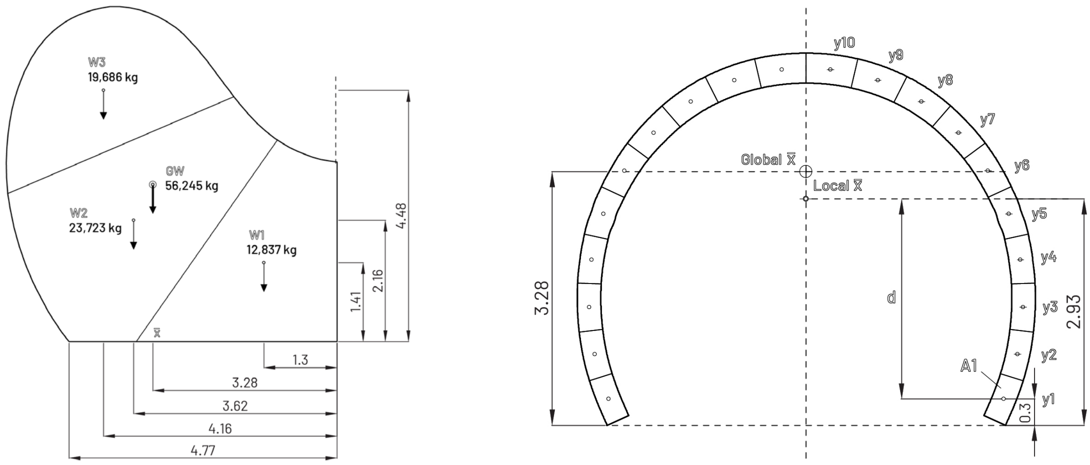

Figure 3: a. Centroids and masses for each of the three segments of the sculpture; b. Plan view showing sections analyzed at the base of the structure. [Davis]

Table 2: Data on segments analyzed at the base of the structure to estimate section properties.

Segments	A	A*y	Distance from centroid (Ad^2)
Total	2.15 m^2 (23.12 ft^2)	2.93 m (115.3 in)	5.46 m^4 (13,120,658 in^4)

With a total area at the base of the structure of 4.29 m^2 (6,658.6 in^2), the axial compressive stress under dead load is:

$$\frac{P}{A} = \frac{551.6\,kN}{4.29\,m^2} = 0.13\,N/mm^2 \quad (1)$$

$$\left(\frac{P}{A} = \frac{124\,k}{6658.6\,in^2} = 18.6\,psi\right)$$

Due to the eccentricity of the global centroid from the local centroid at the base, there is a resulting bending moment M at the base. A stress analysis is performed at the base of the structure to compute bending stresses. The moment can be computed for $\bar{e}$ as eccentricity and M as moment (P*e):

$$\bar{e} = 3.28\,m - 2.93 = 0.35\,m \quad (2)$$

$$(\,\bar{e} = 129.2\,in - 115.3\,in = 13.9\,in\,)$$

$$M = 551.6\,kN \cdot 0.35\,m = 193.1\,kNm \text{ (kNm)} \quad (3)$$

$$(\,M = 124k \cdot 13.9\,in = 1{,}723.6\,k - in\,)$$

To estimate the moment of inertia (m^4; in^4) for the base section, the local moment of inertia is neglected and the Ad^2 terms are computed according to the parallel axis theorem. This moment of inertia I is estimated as 5.46 m^4 (13,121,000 in^4) (Table 2). Neglecting the local moment of inertia $bh^3/12$ terms results in an over-estimate of the bending stresses; the actual bending stresses will be somewhat lower. The combined axial and bending stress on the base is found from $\frac{P}{A} \pm \frac{My}{I}$, where y is the distance from the local centroid at 2.93 m (115 in) and I is the moment of inertia of the horseshoe section (Figure 4).

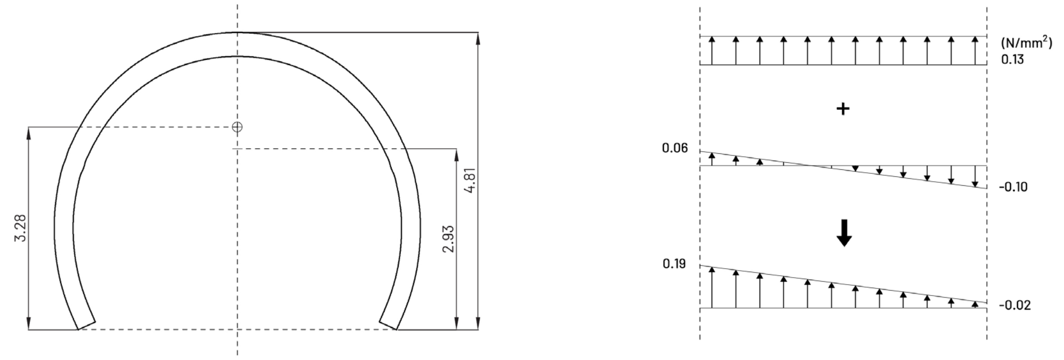

Figure 4: Stress diagrams under dead load, including axial stress, bending stress and combined stress (compression is positive and tension is negative). [Davis]

The total stress magnitudes under dead load are the sums of the axial and bending stresses: at the arch opening, $\sigma_{min} = 0.02$ N/mm² (3.5 psi), and at the back of the structure, $\sigma_{max} = 0.19$ N/mm² (28.1 psi). Also note that the base of the sculpture is fully in compression under dead load.

Globally, there are very low stresses at the bottom of the structure. When we consider the compressive strength of the brick (indicated by the manufacturer Taylor Clay) as 65 N/mm² (9,400 psi), this gives a considerable safety against crushing of approximately 330 under dead load.

3.1.1. Earthquake loads up to 0.15g

To evaluate the lateral loading capacity of the structure, we consider earthquake loads with a peak ground acceleration of 0.15g. This would safely account for other anticipated live loads, such as wind loads. This can be approximated as an equivalent static load of 0.15 x the self-weight of the sculpture, which gives a horizontal force of 82.7 kN (18.6 kips) applied globally at a height of 2.8 m (110.2 in), to give a maximum moment of 231.6 kNm (2,050 kip-in). The critical direction of loading would increase the tensile stress at the opening rather than at the rear of the base.

Due to a seismic overturning moment of 231.6 kNm (2,050 kip-in), additional bending stress is: $\pm \frac{My}{I}$

Table 3: Bending stress due to earthquake load of 0.15g equivalent static.

	y	σ
at opening	2.93 m (115.3 in)	-0.12 N/mm² (-18.0 psi)
at back	1.84 m (72.6 in)	0.08 N/mm² (11.3 psi)

This is combined with the dead load to evaluate the total stress at the arch opening and at the back of the structure, respectively as σ_{front} = -0.10 N/mm² (-14.5 psi) and σ_{rear} = 0.27 N/mm² (39.5 psi) (Figure 5). This demonstrates that a large earthquake could cause tensile forces at the base of the sculpture near the opening.

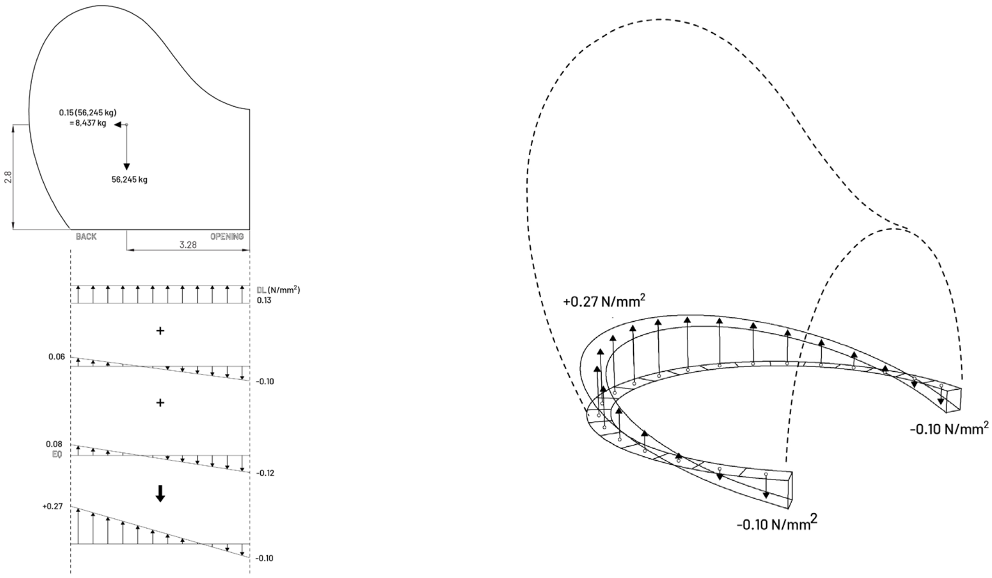

Figure 5: a. Total stresses in the structure due to dead load combined with earthquake load of 0.15g in the most unfavorable direction; and b. Axonometric diagram showing combined stresses at the base of the structure due to a horizontal static load of 0.15g simulating a large earthquake. [Davis]

These values for the overall behavior of the structure approximately correspond with the FEA modeling performed by Silman. As we demonstrate the potential for uplift at the arch opening of the structure, adequate steel tying details were recommended at this location, though the forces would be quite small even due to a large earthquake.

This considers the reaction stresses at the base of the structure to assist with the design and detailing of the foundation connections. Because of the grid of steel reinforcing in the center of the shell, small local tensile stresses in the sculpture can be resisted by the steel grid. In addition, the self-supporting nature of the construction process means that much of the dead load will be carried through arching action during construction. The analysis above demonstrates that the stresses are very low and that the sculpture is predominantly acting in compression at the base.

3.2. Reinforcement design

Additional analysis was performed to design the steel reinforcement of the core and further validate the stability analysis. As a permanent sculpture, the structure must resist all applicable dead, live, wind, snow, and earthquake loads as prescribed by the 2020 Building Code of New York State.

The Storm King Art Center is in a "special wind region" near mountainous terrain where higher wind-speed anomalies are known to exist. The design wind speed taken from the building code was determined verified with a local building department and review of regional climatic data. The geometry of the structure catches the wind like a sail; a single large opening on one side allows wind pressure to build up inside without a release. Loads were amplified based on code requirements for this enclosure criteria; any potential benefits of the tube holes were neglected in the wind calculation for conservatism. New York State is in a moderate seismic region and earthquake loads were calculated using an equivalent lateral force method.

The structural behavior transitions from that of an arch to that of dome, with zones of tension that develop at the changes in geometry. Figure 6 is a simplified diagram to show how the tension (blue) and compression (green) forces develop within the rebar. At the dome, circular hoop forces develop in tension to resolve the compressive forces of the dome geometry. The front arch is primarily in compression with a lateral thrust at the base, which is resolved by the concrete foundation.

The reinforced concrete core was designed to resist the maximum factored tension and bending forces in accordance with ACI 318. The specified steel #3 rebar centered on the 0.1 m (4 in) thick concrete core and spaced at 0.3m (12 in) on center was found to be more than adequate for all load combinations as well as temperature and shrinkage reinforcement.

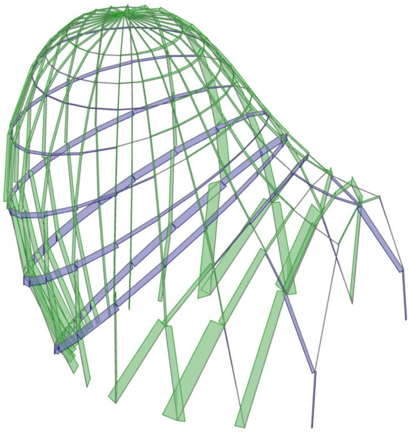

Figure 6: The tension (blue) and compression (green) forces develop within the rebar structure [Silman]

The steel rebar cage is necessary for construction guidance, temperature control, and for tensile reinforcement in the overhanging portion of the shell. Figure 6 identifies zones of tension where continuity of the steel reinforcement bars was necessary. Continuity of lap splices in these zones was coordinated with the steel fabricator. The steel cage also played an important role in the constructability of the structure, as it provided a template for the geometry and additional reinforcement during temporary conditions for loading conditions that would occur as the walls were being constructed before the restorative load of the dome was in place.

The structure is supported at its base with continuous reinforced concrete foundation walls on spread footings. The footings extend down to frost depth on compacted soil per local requirements. Under wind and earthquake loads, uplift forces develop at the juncture between the shell structure and the reinforced concrete walls. The dowels into the foundation walls were designed to transmit these loads. No net uplift occurs under any load combinations at the base of the foundation because of the significant restorative mass of the structure.

3.3. Shear analysis of the reinforced cement tubes

It was critical to ensure that the brick masonry would not be at risk of spalling off in the future, causing a risk to museum visitors as well as the performance of the structure. Modern building code requires masonry veneer to be anchored to back-up wall at regular intervals; however, in this sculpture, the inner and outer masonry wythes are not acting as a veneer – they are part of the primary structure. The performance is more analogous to a multi-wythe masonry wall tied together with brick headers, as previously described. It was necessary to justify this performance analytically, especially in the zones of tension.

First, the adhesion between the concrete core and the brick was analyzed on its own. The maximum shear flow across the two primary interfaces was found to be well below the allowable limits of the prescribed mortar. Regardless, a mechanical connection was necessary between the layers to not solely rely on friction. It was decided to scour shear keys into the fiber-reinforced cement tubes within the concrete zone to allow for locking of the center core (via the key) to the outer cores (via the friction between the fiber-reinforced cement tubes and the masonry). The key was sized to take the full shear flow of the interface. The keys covered approximately 3% of the structure, located on a 0.9 m by 0.9 m (3 ft by 3 ft) grid.

Additional structural analysis also confirmed that the center concrete core can support the full load of the entire structure on its own, with the inner and outer shells hung from it. This would account for a scenario of extreme mortar deterioration to the point where the structure no longer acted monolithically.

It was confirmed that the existing 10 cm (4 in) thick concrete shell on its own can resist all the structural loading. This allowed for additional structural redundancy. Regularly cyclical maintenance of the structure is key to its long-term performance, especially given the unique nature of the structural system and the lifespan of brick mortar components.

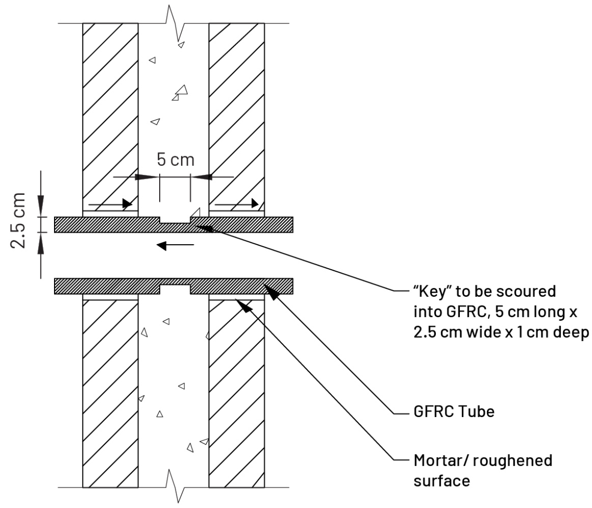

Figure 7: Shear key in fiber-reinforced cement tubes [Davis and Silman]

4. Conclusion

In summary this extraordinary sculpture by Martin Puryear was realized with a novel combination of approaches in structural design and construction. 'Lookout's' form-finding was in wood, carved by the hand of a master craftsman. Its structural design employed first-principles equilibrium analysis, analytical methods for the design of the steel cage, and shear analysis for the tying capacity of the fiber-reinforced cement tubes. And its translation to scale in reinforced brick masonry involved the adaptation of traditional masonry techniques (Nubian vaulting and mechanical tying), minimal formwork systems and the use of reinforcement as guidework, material innovation in rapid-setting, durable mortars, and mastery in the art of bricklaying. This sculpture has drawn deeply from the craft of the past, and it will look long into the future in the unique landscape of Storm King.

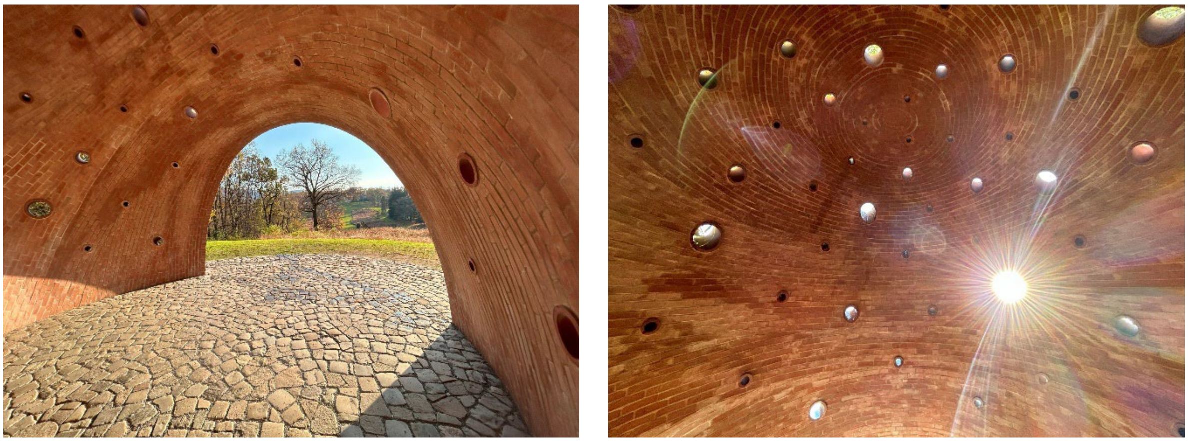

Figure 8: Completed "Lookout" sculpture at Storm King Art Center [Photos by Lara Davis]

Acknowledgements

The authors would like to acknowledge the curatorial team at Storm King Art Center (Amy Weisser, Nora Lawrence, Adele Goldsmith), the facilities team at Storm King (Mike Seaman), the masonry crew (Lara Davis, Rob Horton, Scott Cafarella, Mario Magana, Aaron Getman-Pickering), Kurt Wulfmeyer and Christopher Powers of KC Fabrications, Silman, Reed Hilderbrand Landscape Architecture, Jeanne Englert, David Collens, John Stern, Steve Blankenbeker and Taylor Clay Products, Edison Coatings, David Kucera Inc. MIT students Sabrina Madera, Jaime Osuna, Katie Rotman, Justin Brazier, Charlie Janson and Tejumola Bayowa contributed to 3D modeling and estimating in the summer of 2021 and 2022, and their work was partially supported by the Margaret MacVicar Fund at MIT.

References

[1] M. Puryear, J. P. Stern, et al, *Martin Puryear: Lookout*, Storm King Art Center, Gregory R. Miller & Co., 2024.

[2] J. Elderfield and M. Auping, *Martin Puryear*, The Museum of Modern Art, 2007.

[3] H. Fathy, *Architecture for the poor*, University of Chicago Press, 1976.

[4] J. Ochsendorf, *Guastavino vaulting: The art of structural tile*, Princeton Architectural Press, 2010.

[5] B. Bracegirdle, *The Archaeology of the Industrial Revolution*, Heinemann Educational, 1973.

[6] J. Ochsendorf, "Engineering of a Brick Sculpture," A+U, vol. 22:12, no. 627, pp. 86-87, 2022.

[7] S.Maïni and L. Davis, *Building with Arches, Vaults and Domes: Training Manual for Architects and Engineers*, Auroville Earth Institute, 2016.

[8] L. Davis, M. Varma, S. Maïni, "Sharanam: Case study of a 15 meter span earthen conical vault", Structures, vol. 18, pp. 10-19, 2018.

[9] R. Anger and L. Fontaine, *Bâtir en terre : du grain de sable à l'architecture*, Belin, Cité des sciences et de l'industrie, 2009.

[10] H. Houben and H. Guillaud, *Earth construction: a comprehensive guide*, Practical Action, 1994.

[11] R. Besenval, *Technologie de la voûte dans l'orient ancien : Vol 1, Vol 2*, CNRS, 1984.

[12] T. Rinaldi and R. Yasinsac, *Hudson Valley ruins: forgotten landmarks of an American landscape*, University Press of New England, 2006.

[13] F. Graham and T. J. Emery, *Audels Masons and Builders Guide*, No. 1-4, Theo. Audel & Co., 1924.

[14] G. Villahermosa, *Rosendale*, Arcadia Publishing, 2019.