Steam-Formed Cellulose Domes: Morphogenetic Construction Using Intermittent Steam Inflation and Magnet-Directed Reinforcement

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March 16, 2026

Abstract

This paper proposes a morphogenetic construction method for lightweight architectural shells using steam-inflated cellulose composites and magnetically guided reinforcement networks. The technique begins with a flexible membrane coated in cellulose slurry anchored to a perimeter ring. Intermittent steam pulses inflate the membrane while heat drives evaporation and fiber alignment. During inflation, reinforcement cables embedded with magnetically responsive nodes are guided by an external magnetic field, producing differentiated ribbing that stabilizes the emerging shell.

Unlike conventional dome construction, which relies on rigid formwork or prefabricated elements, the proposed method allows geometry to emerge from coupled pressure, material transport, and reinforcement guidance. The resulting structure behaves as a ribbed cellulose shell whose strength derives from curvature, fiber alignment, and embedded tension members.

A simplified mathematical model is presented describing shell evolution under pulsed pressure, cable tension, and magnetic steering. The model illustrates how rib networks arise naturally from anisotropic reinforcement during the inflation process.

Because the primary materials consist of plant fiber, water, and heat, the method may offer a pathway toward low-energy, biodegradable construction. Potential applications include temporary shelters, ecological pavilions, and distributed fabrication systems in resource-constrained environments.

1

Contents

1 Introduction

Architectural domes represent one of the most efficient structural forms for enclosing space. Curvature distributes loads evenly across a shell, allowing large spans to be constructed with relatively small amounts of material. However, conventional dome construction typically requires extensive formwork, scaffolding, or prefabricated components to impose the desired geometry during fabrication.

Biological systems demonstrate an alternative approach to shell formation. Many natural structures arise not from rigid molds but from pressure-driven expansion combined with fiber reinforcement. Plant stems, fungal fruiting bodies, insect nests, and seed pods all develop through processes in which internal pressure interacts with anisotropic fiber networks and environmental drying conditions.

Inspired by these morphogenetic processes, this paper proposes a construction method in which architectural shells are formed through intermittent steam inflation of a cellulose composite membrane. Cellulose is the most abundant structural polymer on Earth and forms the basis of paper, plant fibers, and numerous biodegradable composites. When combined with water and heat, cellulose fibers can be deposited as a slurry that becomes rigid as moisture evaporates.

In the proposed system, a cellulose slurry is applied to a flexible membrane attached to a circular foundation ring. Steam introduced beneath the membrane expands the shell while simultaneously heating the cellulose layer. Repeated cycles of inflation and drying allow the fibers to align and lock into position, gradually producing a self-supporting dome.

A key feature of the method is the use of reinforcement cables embedded within the shell during the inflation process. These cables are connected to magnetically responsive attachment nodes whose positions can be adjusted using external magnetic fields. As a result, reinforcement ribs can be guided dynamically while the structure is forming, allowing the dome to develop differentiated structural pathways without rigid formwork.

This approach transforms dome construction from a process of imposed geometry into a process of guided material evolution. Steam pressure drives expansion, cellulose fibers supply the structural medium, and magnetically guided cables steer reinforcement topology.

The paper develops three principal components of this concept. First, it describes the construction process and material system used to produce steam-formed cellulose

domes. Second, it introduces a simplified mathematical model for shell evolution under pulsed pressure and reinforcement forces. Third, it discusses architectural implications and potential applications of the technique.

The central claim of this work is that architectural shells can be grown rather than assembled. By coupling pneumatic expansion, fiber-based materials, and field-guided reinforcement, it becomes possible to fabricate dome structures whose geometry emerges from physical processes rather than rigid templates.

2 Background

2.1 Pneumatic and Inflatable Architecture

The use of air pressure as a structural medium has a substantial history in twentieth-century architecture. Pneumatic structures exploit the capacity of pressurized membranes to enclose large spans without internal supports, reducing material consumption and enabling rapid deployment. Among the most influential practitioners of this approach was Frei Otto, whose work on tensile and pneumatic forms explored the boundary between structural engineering and natural morphology. Air-supported domes and textile shells demonstrated that stable enclosures could be maintained through continuous internal pressure, anchored at their perimeters to resist lateral thrust.

Despite their elegance, pneumatic structures exhibit well-documented limitations. Continuous pressurization is required to maintain form, making them dependent on mechanical systems and vulnerable to sudden depressurization. Their structural stiffness is comparatively low, and permanent applications typically require supplementary rigid elements. The method proposed here departs from purely pneumatic precedent by using steam pressure not to maintain a permanent inflated state but to drive a material phase transition, after which the cellulose shell becomes self-supporting without further pressurization.

2.2 Fiber-Based Construction Materials

Cellulose fibers have been used in construction materials across a wide range of scales and applications. Paper, cardboard, and plant-fiber composites offer favorable stiffness-to-weight ratios and are compatible with low-energy fabrication processes.

Relevant mechanical properties include tensile strength, which in aligned cellulose fibers approaches that of certain metals by weight, hygroscopic behavior, which governs the absorption and release of moisture during drying, and thermal response, which determines how fiber networks reorganize under heat.

Of particular relevance is the behavior of cellulose slurries under drying conditions. As moisture evaporates, cellulose fibers form hydrogen bonds and the material stiffens substantially. This transition from a plastic, deformable state to a rigid, load-bearing structure is the fundamental mechanism exploited in the steam-formed dome process. The drying transition is irreversible under normal conditions, ensuring that once geometry is locked in, it is preserved.

2.3 Biological Analogues

Natural systems that construct shell-like structures through pressure-driven fiber alignment provide strong conceptual precedents for the proposed method. Plant stems develop structural integrity through turgor pressure combined with oriented cellulose microfibrils in the cell wall, which constrain the direction of growth. Fungal fruiting bodies grow into characteristic shapes through differential pressure and wall stiffening in localized regions. Insect nests, particularly those constructed from chewed plant fiber, produce ribbed cellulose shells whose geometry encodes mechanical efficiency.

A common pattern runs through all these cases: internal pressure combined with a distributed fiber network and spatially differentiated drying or stiffening produces a stable, load-bearing shell. The proposed construction method is an engineered analogue of this biological logic, substituting steam for turgor, cable reinforcement for cell-wall microfibrils, and magnetic steering for chemical differentiation.

3 Construction Concept

3.1 Basic Inflation System

The elementary construction unit consists of four components: a foundation ring, a flexible membrane, a cellulose slurry layer, and a steam injection port. The foundation ring anchors the perimeter of the structure and provides a boundary condition against which membrane tension can act. The flexible membrane rests

initially flat within or upon this ring and serves as a temporary substrate for the cellulose layer. The slurry is distributed across the membrane surface before inflation begins, and the steam injection port is located beneath the membrane.

The process unfolds in five stages. First, the cellulose slurry is applied to the upper surface of the membrane, forming a wet composite layer of approximately uniform initial thickness. Second, steam is injected beneath the membrane, creating a pressure differential that drives the membrane upward. Third, the membrane expands into a dome-like shape, stretching the cellulose layer with it. Fourth, the combination of heat and moisture induces fiber alignment and initiates drying in the outer portions of the shell. Fifth, the shell dries and stiffens progressively from the exterior inward, eventually achieving sufficient rigidity to be self-supporting.

3.2   Intermittent Steam Pulsing

A critical feature of the system is that steam is applied intermittently rather than continuously. The pulsed pressure profile allows the construction process to alternate between phases of active inflation and phases of relaxation, cooling, and drying. This rhythm is essential because it permits repositioning of the cable reinforcement network between pulses, enables material redistribution as the shell adjusts its geometry, and allows partial drying to consolidate gains in curvature before the next expansion cycle.

The pressure profile is modeled as

$$P(t) = P_0 + \Delta P \, \sigma(t), \tag{1}$$

where P_0 is a baseline pressure, ΔP is the incremental pulse amplitude, and $\sigma(t)$ is a piecewise-smooth pulsed function. A concrete model for σ is

$$\sigma(t) = \sum_{k=0}^{N} \chi_{[t_k, t_k+\tau_k]}(t), \tag{2}$$

where $\chi_{[t_k,t_k+\tau_k]}$ is the characteristic function of the k-th inflation interval of duration τ_k. Between pulses the pressure returns to P_0, allowing the structure to partially consolidate.

3.3 Rib Formation

Rather than producing a smooth uniform shell, the steam-formed dome naturally develops reinforcing ribs. These arise from three cooperating sources. Cable reinforcement introduces localized pathways of higher tension, which resist lateral spreading and attract fiber deposition. Thermal gradients during steam pulsing produce differential drying, so regions nearer the membrane surface stiffen before interior regions, creating seams of higher stiffness. Tension along cable paths during inflation stretches the slurry preferentially, thickening the shell at reinforced seams.

The resulting structure resembles the vascular architecture of plant tissue, in which load-bearing bundles are embedded in a softer parenchymal matrix. In both cases the ribbed geometry is more efficient than a uniform shell of equal mass: the ribs carry tensile and compressive loads along stress paths while the interrib surface carries in-plane membrane stresses.

4 Thermodynamic Role of Steam

The use of steam rather than air or liquid pressure is central to the operation of the steam-formed dome process. Steam serves simultaneously as a pressure medium, a heat transport mechanism, and a phase-transition driver for the cellulose composite. This threefold role is not incidental; it is the physical condition that makes the method coherent as a unified process rather than a combination of separately controlled operations.

From a thermodynamic perspective, steam introduces both mechanical work and thermal energy into the system. The pressure component drives membrane inflation while the latent heat of condensation accelerates fiber bonding and moisture redistribution within the slurry layer. Let T_s denote the steam temperature and L_v the latent heat of vaporization of water. The energy delivered per unit mass of steam that condenses on the cellulose surface is

$$E = c_p(T_s - T_0) + L_v, \tag{3}$$

where c_p is the specific heat of water vapor and T_0 is the ambient temperature of the membrane. Because L_v is large relative to the sensible heat term $c_p(T_s - T_0)$ under typical operating conditions, steam condensation releases substantial thermal energy directly into the cellulose network. This localized heating promotes fiber mobility

during inflation and accelerates the subsequent drying phase as steam supply is interrupted between pulses.

The thermodynamic contrast with the two obvious alternatives is instructive. Air pressure alone could inflate the membrane but would not produce the thermal conditions required for rapid cellulose bonding, and without heat the slurry would remain plastic and unable to consolidate gains in curvature between pulses. Liquid water pressure could supply mechanical force but would saturate the slurry and inhibit drying entirely, preventing the phase transition from plastic to rigid state that gives the dome its final stiffness.

Steam therefore occupies a unique thermodynamic regime in which pressure-driven geometric formation and fiber stiffening occur within the same physical process, driven by the same input. This coincidence is not a convenience but a structural feature of the method: it means that the rate of inflation and the rate of material consolidation are coupled by the steam supply rate rather than requiring independent control. The pulsed pressure profile of equation (1) is also, implicitly, a pulsed thermal profile that governs the rate of fiber bonding and moisture evaporation throughout the construction sequence.

5 Magnet-Directed Cable Reinforcement

5.1 Cable Network Representation

The reinforcement system is formalized as an embedded graph

$$\Gamma = (V, E) \tag{4}$$

on the dome surface, where V denotes the set of attachment nodes and E denotes the set of cable segments. Each cable segment $e \in E$ runs along the shell surface between two nodes and contributes tensile stiffness along its path. Each node $v \in V$ is a point at which cables meet, change direction, or terminate at the foundation ring.

The tension energy associated with a cable segment e is

$$\mathcal{E}_{\text{cable}}(e) = \frac{1}{2} T_e \int_e |\partial_s X|^2 \, ds, \tag{5}$$

where T_e is the effective tension coefficient and s is arclength along the path. The total cable energy is

$$\mathcal{E}_{\text{cable}}(\Gamma) = \sum_{e \in E} \mathcal{E}_{\text{cable}}(e), \tag{6}$$

and the cable-induced force acting on the shell is the variational derivative

$$f_{\text{cable}} = -\frac{\delta \mathcal{E}_{\text{cable}}}{\delta X}. \tag{7}$$

5.2 Magnetic Steering

Selected nodes in V carry magnetically responsive elements with magnetic moments m_i. An externally applied field $B(x, t)$ induces a force on each such node given by

$$F_m \propto \nabla(m_i \cdot B), \tag{8}$$

which drives the node toward regions of greater magnetic energy density. At the level of the full node set, a schematic magnetic potential is

$$\mathcal{E}_{\text{mag}} = -\sum_i m_i \cdot B(X(v_i, t), t), \tag{9}$$

and the resulting guidance force is

$$f_{\text{mag}} = -\frac{\delta \mathcal{E}_{\text{mag}}}{\delta X}. \tag{10}$$

By adjusting the spatial configuration of the external field between steam pulses, the operator can reposition attachment nodes while the shell surface is still plastic, thereby steering the trajectory of individual ribs.

5.3 Adaptive Rib Topology

Magnetic steering enables a range of rib geometries that would be difficult or impossible to achieve with fixed formwork. Radial ribs running from the apex to the foundation ring distribute meridional loads in the manner of a ribbed vault. Spiral ribs engage the torsional stiffness of the shell and can compensate for asymmetric loading conditions. Branching ribs allow reinforcement density to vary across the surface in response to localized stress concentrations. In the limit, the reinforcement topology can be configured to approximate principal stress trajectories, making the

11

rib network a direct material encoding of the shell's stress state.

In this sense, the dome's architecture is field-guided rather than mold-defined. The magnetic field is an active design parameter, not merely a passive boundary condition.

6 Robotic Fabrication Possibilities

Although the conceptual process described in this paper can be executed with manual control, the system is well suited to robotic fabrication. Steam injection, magnetic field steering, and reinforcement cable adjustment can each be automated through a closed-loop control system that monitors shell geometry continuously during inflation and responds to deviations from target curvature and rib trajectories.

Let the evolving shell surface be reconstructed from sensor data as $\Sigma(t) = X(\xi^1, \xi^2, t)$. A robotic controller equipped with range-sensing instruments, such as structured-light scanners or laser profilometers, can estimate local mean curvature H, shell thickness h, and stress trajectories at each pulse interval. Magnetic field actuators positioned around the construction perimeter can then reposition reinforcement nodes to approximate optimal rib paths as computed from the current surface estimate.

Such a system effectively implements a form of real-time structural form-finding in which geometry, reinforcement topology, and material distribution co-evolve during fabrication rather than being specified in advance. The control law can be written schematically as a feedback loop: at each inter-pulse interval, the current surface $\Sigma(t)$ is measured, the deviation from a target curvature field is computed, and magnetic actuator positions are updated to minimize that deviation over the following pulse. This is formally analogous to model-predictive control applied to a distributed parameter system whose state is the shell embedding X and whose input is the magnetic field configuration $B(x, t)$.

The robotic fabrication framework also opens the possibility of multi-objective optimization during construction. If strain sensors are embedded in the reinforcement cables, real-time load data can be used to steer ribs toward principal stress trajectories on the current surface, implementing in hardware the geodesic alignment argument of Section 8. This approach aligns with recent developments in robotic construction in which physical processes such as extrusion, deposition, and tension-net formation are guided by continuous feedback rather than static design blueprints, and it

extends those precedents to a material system in which the structural medium itself undergoes an irreversible phase transition during fabrication.

7 Prototype Fabrication Method

7.1 Materials

The prototype construction uses the following material components: cellulose fiber slurry composed of plant pulp and water; a flexible membrane substrate; reinforcement cables with magnetically responsive nodes; paper honeycomb panels; a steam injection system; and a circular foundation ring. All primary structural material is cellulose-based, allowing the structure to remain biodegradable and largely renewable.

7.2 Stage One: Foundation and Membrane Setup

Construction begins with a circular or polygonal foundation ring that anchors the perimeter of the structure. A flexible membrane is attached to the ring and initially rests flat; this membrane serves as a temporary substrate upon which the cellulose shell will form. A layer of cellulose slurry is distributed across the membrane surface to an approximately uniform initial thickness before any other operations begin.

7.3 Stage Two: Installation of the Reinforcement Network

A cable reinforcement network $\Gamma = (V, E)$ is installed on the membrane before inflation begins. Selected nodes carry magnetically responsive elements, so that the network can be repositioned during inflation by adjusting the external field configuration. The initial placement of the network determines the starting topology of the rib system, which then evolves dynamically as steam pulses proceed.

7.4 Stage Three: Honeycomb Scaffold Placement

Before steam inflation begins, a lightweight paper honeycomb lattice is placed on top of the cellulose slurry layer. Paper honeycomb structures are widely used in lightweight panels owing to their high stiffness-to-weight ratio. In this application

the honeycomb functions as a temporary scaffold that stabilizes the shell during early inflation.

The honeycomb scaffold is represented as a cellular lattice

$$\mathcal{H} = \{C_1, C_2, \ldots, C_n\} \tag{11}$$

where each cell C_i is a hexagonal support unit. The scaffold performs two important functions: it distributes loads during the early inflation phase before the outer shell has developed sufficient stiffness, and it introduces a structured cellulose reservoir that will later dissolve and redistribute material to form the interior shell layer.

7.5 Stage Four: Steam Inflation

Steam is introduced through a central injection port beneath the membrane. The pressure profile is pulsed according to equation (1). Each pulse simultaneously drives membrane expansion, induces fiber alignment in the cellulose slurry, compresses and heats the honeycomb lattice, and adjusts cable tension. Between pulses the structure relaxes, allowing material redistribution and partial drying to consolidate the geometry achieved in the preceding cycle.

7.6 Stage Five: Honeycomb Dissolution and Inner Layer Formation

As steam pressure and moisture accumulate, the paper honeycomb scaffold begins to soften and partially dissolve. High-pressure steam drives cellulose fibers from the honeycomb walls into the inner surface of the dome shell. The dissolution dynamics are approximated by

$$\frac{dM_H}{dt} = -\lambda M_H, \tag{12}$$

where $M_H(t)$ is the remaining honeycomb mass and λ depends on steam temperature and pressure. Rather than disappearing completely, the honeycomb material redeposits as a secondary fiber layer on the interior surface of the dome. The resulting structure therefore contains two layers: an outer inflation shell formed by the original slurry, and an inner reinforcement layer derived from the dissolved honeycomb.

This staged dissolution converts the scaffold from a temporary support structure into an integral component of the final dome shell, a transition that is fundamental

to the morphogenetic logic of the method.

7.7 Stage Six: Drying and Structural Locking

Once steam inflation ceases, the dome is allowed to dry. Moisture content decays approximately as

$$\frac{dm}{dt} = -km, \tag{13}$$

until a critical moisture level m_c is reached, at which point the cellulose fibers bond and the dome becomes self-supporting. The reinforcement cables remain embedded in the shell, forming rib lines that distribute loads across the dome surface.

7.8 Resulting Structure

The final structure consists of three interacting layers: an outer cellulose shell formed during inflation, an inner fiber layer produced by dissolved honeycomb material, and a rib network defined by cable reinforcement. Together these layers produce a lightweight composite dome whose strength arises from curvature, fiber reinforcement, and tensioned ribs rather than massive material thickness.

8 Geometric Role of Honeycomb Scaffolds

The use of paper honeycomb structures as temporary scaffolds is motivated by both geometric and mechanical considerations beyond the material properties already described.

8.1 Hexagonal Tiling Efficiency

A honeycomb lattice consists of repeating hexagonal cells. Among regular tilings of the plane, hexagonal packing provides the maximum enclosed area for a given perimeter length, a classical result known as the honeycomb conjecture, proved in full generality by Hales in 2001. If the edge length of each hexagonal cell is a, then the area of each cell is

$$A_c = \frac{3\sqrt{3}}{2}\,a^2, \tag{14}$$

15

and the total scaffold area for n cells is $A_H = nA_c$. This efficient packing allows the scaffold to cover large surfaces while remaining lightweight and easily deformable during inflation. The consequence for the dome process is that the honeycomb delivers the maximum structural coverage per unit of cellulose mass consumed, maximizing the inner reinforcement layer derived from its dissolution.

8.2 Compatibility with Dome Curvature

When the membrane begins to inflate, the originally planar honeycomb lattice must adapt to a curved geometry. Small elastic deformation of hexagonal cells allows the lattice to conform to surfaces of positive Gaussian curvature. The cells elongate along stress directions, producing an anisotropic deformation pattern that naturally aligns with the dome's principal stress trajectories. This behavior makes the honeycomb a passive stress-alignment device during the early inflation phase, before the magnetic cable network has been repositioned to define explicit rib paths.

8.3 Steam-Induced Dissolution and Inner Layer Formation

The dissolution process described in Section 5.5 can be understood geometrically as well as chemically. Because the honeycomb wall structure is periodic, dissolution occurs along a regular lattice of seams, releasing fibers in a spatially organized pattern rather than randomly. The dissolved fibers therefore accumulate on the inner surface with a faint but coherent spatial structure that reflects the original hexagonal geometry. If the outer shell thickness is $h_o(x)$ and the inner deposited layer thickness is $h_i(x)$, the total local shell thickness is

$$h(x) = h_o(x) + h_i(x). \tag{15}$$

The honeycomb seam traces in h_i can function as secondary reinforcement pathways even after the primary hexagonal geometry has been lost to dissolution.

8.4 Structural Interpretation

The honeycomb scaffold performs three sequential structural roles: early-stage stabilization of the wet cellulose shell, geometric guidance during inflation through passive stress alignment, and conversion into inner reinforcement material. This

threefold function exemplifies the design principle of staged material transformation that runs through the entire construction method.

9   Geodesic Alignment of Reinforcement Ribs

The reinforcement ribs that emerge in the steam-formed cellulose dome tend to align with geodesic paths on the shell surface. This alignment arises from the mechanics of thin shells under internal pressure combined with the energy-minimizing behavior of tensioned cables on curved surfaces.

9.1   Geodesics on the Dome Surface

Let the dome surface be represented by a smooth embedding

$$X(\xi^1, \xi^2) \in \mathbb{R}^3 \tag{16}$$

over a parameter domain U. A geodesic curve $\gamma(s)$ on the surface satisfies

$$\nabla_{\dot\gamma}\dot\gamma = 0, \tag{17}$$

where ∇ denotes the surface covariant derivative and $\dot\gamma$ is the unit tangent vector. Geodesics are the critical points of the length functional and represent paths along which tension forces propagate without generating lateral bending stresses. This makes them natural trajectories for load-bearing reinforcement lines.

9.2   Stress Paths in Pressurized Shells

For a pressurized thin shell of approximately spherical geometry and radius R, the classical membrane theory gives principal stresses

$$\sigma_\theta = \sigma_\phi = \frac{PR}{2t}, \tag{18}$$

where P is the internal pressure and t is the shell thickness. The stress field is approximately isotropic on a sphere, meaning that any great circle is a principal stress trajectory and hence a geodesic. For shells of more complex geometry, principal stress trajectories deviate from great circles but remain geodesics of an appropriate

Riemannian metric on the surface. Cables embedded in the pressurized shell and free to slide naturally settle along these geodesic stress paths as energy is minimized.

9.3   Magnetically Guided Geodesic Networks

During steam inflation the cable network $\Gamma = (V, E)$ is embedded on a surface $\Sigma(t)$ that is evolving in time. Magnetic steering applies nodal forces according to equation (7), allowing cables to drift across the shell surface while it remains plastic. As the dome expands, the energy functional governing cable placement tends to drive each cable segment toward a geodesic of the instantaneous surface, since this minimizes the bending component of the cable energy. The magnetic field can reinforce or redirect this tendency, guiding the network toward predetermined structural topologies such as radial, spiral, or branching rib configurations.

9.4   Emergent Rib Geometry

Once drying begins and the cellulose matrix stiffens, the reinforcement paths become fixed as ribs. In the idealized case each rib R_i satisfies

$$R_i \approx \gamma_i, \tag{19}$$

where γ_i is a geodesic on the dome surface. The resulting rib network resembles those found in geodesic domes, tensile membrane structures, and biological shells and plant tissues, but with the critical difference that it has not been imposed by a predetermined geometric subdivision. Instead it has emerged dynamically during the inflation and reinforcement process, adapting to the particular geometry that the shell happened to develop under the given pressure and material conditions.

9.5   Structural Implications

Geodesic rib alignment offers several mechanical advantages. Efficient distribution of tensile loads across the shell reduces bending stresses in reinforcement cables, while natural compatibility with curved dome geometry ensures that ribs do not introduce parasitic lateral forces. The adaptive character of the magnetic guidance system means that reinforcement patterns can respond to variations in shell geometry that were not anticipated in the initial design.

The ribbed cellulose dome therefore combines the load-path efficiency of geodesic structures with the formwork independence of morphogenetic fabrication, occupying a design space distinct from both conventional geodesic domes and conventional pneumatic membranes.

10 Comparison with Conventional Dome Construction

10.1 Concrete Shells

Concrete thin-shell structures achieved their greatest influence in the mid-twentieth century through the work of engineers including Torroja, Candela, and Nervi. Their efficiency derives from the same geometric principle exploited here: curvature allows in-plane membrane stresses to carry loads that would otherwise require much thicker material in bending. However, concrete shells require elaborate formwork to establish their geometry, and the formwork is typically more expensive and labor-intensive than the shell itself. The steam-formed cellulose dome eliminates this requirement by allowing geometry to emerge from the inflation process rather than being imposed by a mold.

10.2 Geodesic Domes

Fuller's geodesic dome achieves structural efficiency through the triangulation of a sphere by a frequency subdivision of a regular polyhedron. This produces a rigid, self-supporting network of struts in which loads are distributed among many redundant paths. The construction process, however, requires precise prefabrication of strut lengths and connection angles, making it difficult to adapt to irregular sites or resource-constrained fabrication environments. The ribbed cellulose dome can approximate a geodesic rib network through the magnetic guidance system, but without requiring prefabrication, since the rib geometry is determined in situ during inflation.

10.3 Frei Otto and Pneumatic Form-Finding

Frei Otto's extensive program of form-finding experiments demonstrated that minimal-energy surfaces, soap films, hanging nets, and pneumatic membranes, can serve as direct design tools for efficient structural forms. The steam-formed dome is in direct intellectual descent from this tradition, sharing the commitment to allowing physical processes to determine architectural geometry. The departure from Otto's work lies in the material phase transition: where Otto's pneumatic forms require continuous pressurization to maintain shape, the steam-formed dome uses pressure as a temporary forming agent and relies on material stiffening to preserve the geometry after pressure is removed.

11 Shell Mechanics and Mathematical Model

11.1 Evolving Shell Geometry

Let the dome surface at time t be represented by an embedding

$$X(\xi^1, \xi^2, t) \in \mathbb{R}^3 \tag{20}$$

defined over a parameter domain $U \subset \mathbb{R}^2$, so that $\Sigma(t) = X(U, t)$. Let n denote the unit normal field and let $H = H(\xi^1, \xi^2, t)$ denote the mean curvature.

A minimal pressure-driven shell model is

$$\partial_t X = \alpha P(t)\, n - \beta H\, n + f_{\text{grav}} + f_{\text{mat}} + f_{\text{cable}} + f_{\text{mag}}, \tag{21}$$

where α is a pressure coupling coefficient, β is a curvature regularization coefficient, f_{grav} is a gravity term, f_{mat} is a material redistribution term, and f_{cable} and f_{mag} are the cable and magnetic forcing terms derived in Sections 4 and 8.

The curvature term $-\beta H n$ regularizes the shell and opposes singular deformation, while the remaining forcing terms introduce anisotropy and structural differentiation. Without cable and magnetic forcing, the system would converge under sustained pressure to a hemispherical shape minimizing mean curvature for a given enclosed volume. The reinforcement terms break this symmetry and drive the emergent geometry toward ribbed configurations.

11.2 Cellulose Thickness Field

Let the local shell thickness be described by a scalar field $h(\xi^1, \xi^2, t) \geq 0$. The thickness evolves under surface diffusion, convective thinning due to stretching, drying, and preferential deposition along cable paths:

$$\partial_t h = D_h \Delta_\Sigma h - \kappa h \, \nabla_\Sigma \cdot (\partial_t X) - \mu h + q_\Gamma, \tag{22}$$

where D_h is a surface diffusion coefficient, Δ_Σ is the surface Laplacian, κ is a stretch-thinning coefficient, μ is a drying coefficient, and q_Γ is a rib deposition source concentrated along cable paths.

The source term q_Γ models the tendency of fibers and binders to thicken around attachment paths and tension seams. Ribs appear where h becomes locally elevated.

11.3 Definition of the Rib Set

Definition 1. *The rib set at time t is the superlevel region*

$$\mathcal{R}(t) = \left\{ (\xi^1, \xi^2) \in U \ : \ h(\xi^1, \xi^2, t) \geq h_c \right\} \tag{23}$$

for a threshold thickness $h_c > 0$.

Ribs are not inserted as separate objects after the fact; they emerge as regions of persistent local thickening induced by the coupled pressure-cable-magnetic dynamics. The threshold h_c can be chosen to reflect the minimum thickness at which a cellulose pathway achieves load-bearing status in a given structural context.

11.4 A Coupled Energy Functional

The system may be summarized by a total effective energy

$$\mathcal{E}_{\text{tot}} = \mathcal{E}_{\text{surf}} + \mathcal{E}_{\text{press}} + \mathcal{E}_{\text{cable}} + \mathcal{E}_{\text{mag}} + \mathcal{E}_{\text{thick}}, \tag{24}$$

where the surface energy is

$$\mathcal{E}_{\text{surf}} = \int_\Sigma \left(\gamma + \eta H^2 \right) dA, \tag{25}$$

incorporating a surface tension term γ and a Helfrich-type bending stiffness ηH^2; the pressure-volume energy is

$$\mathcal{E}_{\text{press}} = -P(t)\,V(\Sigma); \tag{26}$$

and the thickness regularization energy is

$$\mathcal{E}_{\text{thick}} = \int_{\Sigma} \left(\frac{a}{2} |\nabla_{\Sigma} h|^2 + W(h) \right) dA, \tag{27}$$

where $W(h)$ is a double-well potential that permits coexistence of thin interrib regions and thick rib regions as distinct phases.

The shell evolution may be written schematically as a gradient flow,

$$\partial_t X = -\frac{\delta \mathcal{E}_{\text{tot}}}{\delta X}, \qquad \partial_t h = -\frac{\delta \mathcal{E}_{\text{tot}}}{\delta h}. \tag{28}$$

This gives a compact formal statement of the main idea: dome form and rib form co-emerge from an energy landscape shaped by pressure, curvature, cable tension, magnetic steering, and material transport.

11.5   Morphogenetic Interpretation

The resulting dome is neither a purely inflated membrane nor a rigidly prefabricated shell. It is a morphogenetic structure whose geometry arises from guided stabilization. Steam pulses provide global outward forcing; curvature provides regularization; cables provide anisotropic reinforcement; magnetic fields steer the reinforcement topology; cellulose transport thickens selected pathways into ribs. The structure therefore resembles a synthetic analogue of biological growth, in which membranes, tendons, and field-guided differentiation cooperate to produce form.

12   Scaling Considerations

The feasibility of steam-formed cellulose domes depends on how the relevant mechanical and thermodynamic quantities scale with structure size. Establishing these scaling relations is essential before experimental prototypes can be interpreted as evidence about full-scale behavior.

Let R denote the dome radius and t the shell thickness. The total weight of the shell scales approximately as

$$W \sim \rho\, t\, R^2, \tag{29}$$

where ρ is the effective density of the cellulose composite. Membrane stresses in a pressurized shell of approximately spherical geometry scale according to classical thin-shell theory as

$$\sigma \sim \frac{PR}{t}, \tag{30}$$

where P is the internal pressure. Combining these relations reveals an important scaling constraint: for a fixed steam pressure P, the shell thickness must increase proportionally with radius in order to maintain constant membrane stress, so $t \sim R$ and consequently $W \sim \rho R^3$. This is the same cubic scaling that governs uniform-thickness conventional shells and represents the limiting case in the absence of ribbing.

Rib reinforcement modifies this relationship. If the rib network carries a fraction α of the total internal load, the effective membrane stress in the interrib surface is reduced to

$$\sigma_{\text{eff}} = (1 - \alpha)\frac{PR}{t}. \tag{31}$$

Increasing rib density therefore allows larger domes to be constructed without proportional increases in shell thickness, since the ribs absorb load that would otherwise require thicker material. The fraction α depends on rib cross-sectional area, spacing, and alignment with principal stress directions; the geodesic alignment argument of Section 8 suggests that magnetically guided ribs approach the structural optimum for a given rib mass.

The honeycomb-derived inner layer described in Section 7 further enhances scaling performance by increasing bending stiffness without large increases in membrane mass. For a two-layer shell of outer thickness h_o and inner layer thickness h_i separated by an effective distance d, the bending stiffness scales as d^2, so even a thin inner layer at appreciable separation from the outer shell contributes substantially to resistance against buckling under compressive loads.

These relations suggest that small experimental prototypes may scale upward effectively provided that rib density and reinforcement strength increase appropriately with radius and that the inner layer separation is maintained as dome size grows. The principal risk at larger scales is not membrane stress but shell buckling, which depends on the ratio of shell thickness to radius of curvature and is the appropriate target criterion for engineering analysis of full-scale structures.

13   Architectural Applications

The steam-formed cellulose dome is most immediately applicable in contexts where low material cost, rapid deployment, and biodegradability are valued. Lightweight temporary shelters for disaster relief or humanitarian response represent a natural application: the method requires no specialized formwork, relies on materials that can be locally sourced from plant waste streams, and produces structures that decompose without toxic residue once their service life is complete. Ecological pavilions and exhibition structures represent a second class of applications, where the visible rib geometry and the visible cellulose material can serve communicative as well as structural purposes, making the construction logic legible to occupants.

At larger scales, the method may be applicable to distributed fabrication systems in which multiple small domes are assembled into compound structures. Because each dome is formed in situ from a flexible membrane and a slurry, the system is robust to variations in site geometry and does not require transport of rigid preformed elements. The environmental advantages of cellulose over concrete, steel, and synthetic polymers are well established, and the steam-forming process requires only water and heat, both of which can potentially be supplied from renewable sources.

The primary limitations of the method relative to conventional construction are structural strength, moisture resistance, and durability. Cellulose composites are susceptible to degradation in wet environments unless treated with appropriate waterproofing agents, and the load-bearing capacity of a cellulose shell is substantially lower than that of a concrete or steel structure of comparable thickness. These limitations mean that the method is most suitable for applications where light loading, short service life, or environmental decomposability are design priorities.

14   Layered Envelope Construction and Repairability

The steam-formed cellulose dome described in the preceding sections functions primarily as a structural shell. In order to provide thermal stability, durability, and interior finish comparable to conventional building systems, the shell can be augmented with a layered envelope assembly consisting of insulation, paper fiber layers, and gypsum-based coatings. This layered approach allows the dome to

simulate many properties of standard wall assemblies while retaining the advantages of fiber-based construction.

14.1 Layered Wall Concept

The dome envelope may be represented as an ordered sequence of material layers

$$\mathcal{L} = (L_1, L_2, \ldots, L_n) \tag{32}$$

applied from the exterior inward. A representative configuration proceeds as follows: the structural cellulose shell forms the outermost load-bearing stratum; an insulating layer is applied to the interior face of the shell; a paper or fiber composite layer is bonded over the insulation; and a gypsum interior finish completes the assembly. Each layer performs a distinct functional role, and the functional separation between layers is the condition that makes the assembly repairable.

14.2 Thermal Insulation

The insulation layer stabilizes the interior thermal environment of the dome. Materials such as cellulose insulation derived from recycled fiber, aerated fiber composites, or other lightweight insulating media can be applied directly to the interior surface of the structural shell without requiring mechanical fasteners or adhesives incompatible with the cellulose substrate. Let k denote the effective thermal conductivity of the insulation material and d its thickness. The thermal resistance of the layer is

$$R = \frac{d}{k}. \tag{33}$$

Increasing the thickness of the insulation layer improves thermal performance while adding relatively little structural mass, since the layer carries no load. The choice of insulation material can be varied independently of the structural shell, allowing thermal performance to be upgraded without disturbing the primary structure.

14.3 Paper Fiber Intermediate Layer

A paper or fiber composite layer applied between the insulation and the interior gypsum finish performs three functions simultaneously. It distributes minor loads and differential movements across the interior surface, preventing stress concentrations

that would otherwise crack a brittle finish layer. It provides a bonding substrate chemically compatible with gypsum plaster, since both materials are cellulose- or mineral-based and share similar surface chemistry. And it accommodates minor structural movement, including seasonal moisture cycling of the cellulose shell, by absorbing small strains without fracture. Because this intermediate layer is composed of fibers materially similar to those of the structural shell, it integrates naturally into the dome's material system and can be fabricated from the same slurry and drying process at reduced thickness.

14.4   Gypsum Interior Surface

The final interior layer consists of gypsum plaster or gypsum-based panels. Gypsum materials are widely used in conventional construction because they provide smooth finished surfaces, inherent fire resistance arising from the release of bound water under heat, and acoustic damping owing to their moderate density and porosity. Applied to the interior paper layer, gypsum forms a rigid, paintable surface that protects the underlying insulation and fiber materials while creating an interior environment indistinguishable in finish quality from conventional plastered walls. The gypsum layer is the most exposed and therefore the most frequently damaged component of the assembly, a property that motivates placing it last in the sequence and designing it for straightforward removal and replacement.

14.5   Repair-Oriented Design

A central objective of this layered system is to facilitate repair. Conventional building assemblies often integrate structural, thermal, and finishing functions into a single rigid composite layer, making localized repairs difficult, expensive, and likely to cause collateral damage to adjacent material. In contrast, the layered dome envelope separates these functions explicitly.

Let the repair effort for layer L_i be denoted by C_i. Because the layers are modular, accessible from the interior, and bonded rather than mechanically interlocked, the expected repair cost satisfies

$$C_i \ll C_{\text{structure}} \tag{34}$$

for all non-structural layers L_i. Gypsum damage can be addressed by cutting away the affected panel and replacing it without disturbing the paper layer or insulation beneath. Insulation degradation or moisture intrusion can be remediated

by removing the interior finish and intermediate layer locally, replacing the insulation, and refinishing. In no case is it necessary to disturb the structural shell unless the shell itself has been compromised.

This separation of repair domains is not merely convenient; it is a direct architectural expression of the custodial construction philosophy advanced throughout this paper. Just as the dome form was stabilized through iterative regulation during fabrication, the dome's service life is extended through iterative maintenance of its interior layers.

14.6 Implications for Maintainable Architecture

The layered envelope approach aligns the finished building assembly with the morphogenetic logic of the construction process. In both cases, the system is conceived not as a static object to be produced once and preserved unchanged, but as a stratified environment whose components can be repaired, replaced, and adjusted independently over time. The structural shell provides continuity and load-bearing capacity across the building's lifetime. The interior layers provide comfort, protection, and finish, and are designed from the outset to be consumed and renewed.

By combining cellulose structural shells with insulation, paper fiber intermediate layers, and gypsum interior finishes, the dome can approximate the thermal and occupancy performance of conventional buildings while remaining lightweight, repairable, and largely biodegradable. The layered dome envelope is, in this sense, an architectural system designed explicitly for long-term maintenance rather than permanent rigidity.

15 Envelope as System: Moisture, Time, and Material Legibility

The preceding section treated the layered envelope as a functional assembly. This section considers its behavior as a dynamic system subject to moisture cycling, material aging, and the practical demands of long-term habitation.

15.1 Moisture Dynamics in the Layered Shell

Cellulose-based structures interact continuously with ambient humidity. The outer shell, the intermediate paper layer, and even the insulation medium all exhibit hygroscopic behavior: they absorb moisture when ambient relative humidity rises and release it as conditions dry. This behavior can be formalized by introducing a moisture field $w(\xi^1, \xi^2, z, t)$ defined across the thickness coordinate z of the envelope as well as the surface coordinates.

In the steady-state limit, moisture transport through the layered envelope follows a one-dimensional diffusion profile in the thickness direction. Let D_w denote the moisture diffusivity of a given layer. The steady-state moisture concentration satisfies

$$D_w \frac{d^2 w}{dz^2} = 0, \tag{35}$$

subject to boundary conditions at the exterior and interior surfaces. The solution is a linear profile in each layer, with continuity of flux at layer interfaces. The practical implication is that the paper intermediate layer, situated between insulation and gypsum, acts as a moisture buffer: it absorbs excess interior humidity before it can reach the insulation and releases it gradually as interior conditions dry, moderating the amplitude of moisture cycles experienced by the structural shell.

This buffering function is directly analogous to the role of fiber alignment during the construction phase. Just as steam cycles guided fiber organization during dome formation, moisture cycles during occupancy are managed by the layered material structure rather than requiring active mechanical intervention.

15.2 Material Aging and Scheduled Maintenance

Each layer of the envelope ages at a different rate under normal occupancy conditions. The gypsum finish, exposed to impact, cleaning, and humidity fluctuation, has the shortest effective service life and should be treated as a consumable surface to be refinished periodically. The paper intermediate layer, protected from direct exposure, ages more slowly, primarily through gradual fiber degradation under repeated moisture cycling. The insulation layer, if protected from liquid water intrusion, is largely stable over timescales comparable to the building's expected service life. The structural shell, formed of dense bonded cellulose with embedded cable reinforcement, ages most slowly and is designed to outlast multiple cycles of

interior layer replacement.

This gradient of service lives, from short at the interior to long at the exterior, is a natural consequence of the layered assembly logic and can be planned explicitly in the maintenance schedule. Let τ_i denote the expected service life of layer L_i. A rational maintenance program replaces L_1 (gypsum) on a cycle of order years, L_2 (paper) on a cycle of order decades, and inspects L_3 (insulation) and the structural shell on a longer cycle. The cost and disruption of each maintenance event is bounded by the separation principle of equation (20).

15.3   Material Legibility as Architectural Value

The layered envelope makes the building's material logic visible to its occupants. Because each layer is composed of a recognizable, named material with known properties, an occupant can in principle understand what each part of the wall is doing and why it will eventually need attention. Gypsum is a surface finish; it scuffs and cracks and is replaced. Paper fiber is a buffer and bonding layer; it is replaced when the gypsum is damaged deeply enough to reach it. Insulation is a thermal blanket; it is inspected for moisture and replaced if degraded. The structural shell is the building itself; it is monitored and repaired only in the event of significant damage.

This legibility is not merely pedagogical. It creates the conditions under which non-specialist occupants can participate in the maintenance of the building they inhabit. The steam-formed dome, because it is made of familiar, low-cost, widely available materials, does not require specialist contractors for ordinary interior maintenance. This property is particularly significant in the resource-constrained and distributed-fabrication contexts identified in Section 10 as primary applications of the method.

15.4   The Envelope as Ongoing Construction

Taken together, the moisture dynamics, the gradient of service lives, and the material legibility of the layered envelope suggest that the distinction between construction and habitation is less sharp in the steam-formed dome than in conventional buildings. A conventionally constructed building is typically considered finished when the contractor leaves the site. The steam-formed dome, by contrast, remains in a state of managed evolution: its interior layers are periodically renewed, its moisture

equilibrium shifts with the seasons, and its occupants are the proximate agents of its long-term structural continuity.

This is the architectural form of the custodial logic that runs through the paper. Construction is not the imposition of a final state but the beginning of a process of stewardship. The dome does not merely stand; it is kept standing, by the iterative attention of those who inhabit it.

16   Environmental Considerations

The environmental impact of building construction is dominated globally by the production of cement, steel, and fired masonry materials. Ordinary Portland cement production alone is responsible for approximately eight percent of global carbon dioxide emissions, and the embodied energy of structural steel is higher still on a per-kilogram basis. Cellulose-based construction methods offer a potential alternative with substantially lower embodied energy, and the steam-formed dome makes this alternative technically concrete.

Cellulose fibers are derived from plant matter and are therefore part of the short carbon cycle. When incorporated into building structures, the carbon contained in plant fibers is temporarily sequestered within the architectural envelope rather than released into the atmosphere. For temporary or medium-duration structures, this sequestration is real if modest in scale; for structures that are composted or returned to soil at end of life, the carbon completes its cycle without net accumulation in the atmosphere.

Steam-formed domes require primarily water, heat, and plant fiber. If steam generation is powered by renewable energy sources, the construction process may achieve a substantially lower carbon footprint than conventional concrete-based shell construction, since it avoids both the calcination of limestone and the high-temperature sintering processes involved in cement and brick production. The paper honeycomb scaffold and the cellulose slurry can in principle be sourced from agricultural byproducts, paper recycling streams, or purpose-grown fast-rotation fiber crops, each of which has well-characterized environmental profiles in existing lifecycle assessment literature.

The biodegradability of cellulose composites allows structures to be dismantled and returned to the biosphere without generating persistent construction waste. This property is architecturally significant not only at end of life but during the service life:

a dome that is repairable from the same material stock from which it was built closes a material loop that conventional concrete and steel construction leaves open. These characteristics make the proposed method particularly attractive for temporary architecture, ecological installations, and experimental low-impact housing systems, and they reinforce the suitability of the method for the distributed-fabrication contexts described in the applications section.

17   Limitations of the Model

The mathematical model presented in this paper is intentionally simplified and omits several physical processes that may significantly influence the behavior of real structures.

The rheological behavior of cellulose slurries under steam-heated conditions is complex. Wet cellulose exhibits viscoelastic and thixotropic properties that depend on fiber length distribution, concentration, and temperature history, none of which are captured by the diffusion equation used for the thickness field h. In particular, the assumption that thickness evolves by surface diffusion and convective thinning implies a Newtonian-like response that may substantially overestimate the lateral mobility of real slurries, especially at the elevated temperatures induced by steam condensation.

The interaction between cable tension and shell curvature may introduce nonlinear buckling phenomena not described by the membrane approximation adopted in the evolving shell equation. Real thin shells under combined pressure and tension loads can exhibit snap-through instabilities and localized wrinkling modes that are invisible to the gradient-flow model, which assumes smooth deformations. These effects become more pronounced as the dome approaches its final geometry and the cellulose matrix transitions from plastic to rigid.

The honeycomb dissolution model assumes uniform exponential decay governed by a single rate parameter λ. In reality, dissolution depends on local steam flow patterns, cellulose fiber orientation within the honeycomb walls, the spatial distribution of bonding agents in the paper, and the contact angle between steam condensate and the honeycomb cell surfaces. The assumption of spatial uniformity is therefore an oversimplification that may not accurately predict the distribution of the inner reinforcement layer.

Future work should incorporate detailed experimental measurements of slurry rheol-

ogy under steam conditions, numerical simulation of the shell evolution equations with realistic nonlinear material models, and controlled dissolution experiments to characterize honeycomb fiber redistribution as a function of steam temperature, pressure, and exposure duration.

18 Experimental Prototype

To evaluate the feasibility of the steam-formed cellulose dome method, a small-scale experimental prototype can be constructed at laboratory scale. The objective of this prototype is not to achieve full structural performance but to observe the coupled processes of membrane inflation, fiber alignment, rib formation, and honeycomb dissolution under controlled conditions, and to calibrate the model parameters introduced in the preceding sections.

18.1 Prototype Geometry and Materials

A circular foundation ring of radius $R = 1\,\mathrm{m}$ provides the boundary condition for the membrane. A flexible polymer sheet is clamped along the ring perimeter and initially rests flat as the substrate for the cellulose slurry. A cellulose slurry composed of plant fiber pulp and water is applied to the membrane to an initial thickness of approximately $h_0 = 5\,\mathrm{mm}$.

Table 1 summarizes the principal material parameters used in this prototype configuration.

Table 1: Representative material parameters for the small-scale prototype.

Component	Material	Parameter	Value
Cellulose slurry	Plant fiber pulp in water	Initial thickness h_0	5 mm
		Pulp concentration	15–20 % by mass
		Effective density ρ	900–1100 $\mathrm{kg\,m^{-3}}$
Membrane	Flexible polymer sheet	Thickness	0.5 mm
Foundation ring	Steel or aluminium	Radius R	1 m
Honeycomb scaffold	Paper honeycomb panel	Cell edge length a	20 mm
		Panel thickness	15 mm
Steam supply	Saturated steam	Temperature T_s	100–120 °C
		Gauge pressure ΔP	5–20 kPa

Reinforcement cables are placed along radial paths between the center and the

perimeter ring before inflation. Selected cable nodes contain small neodymium magnetic elements that can be repositioned using external hand-held magnets during inflation, implementing the guidance system described in Section 5 at bench scale.

18.2 Steam Inflation Apparatus

Steam is introduced beneath the membrane through a central injection nozzle connected to a small laboratory boiler. The pressure profile follows equation (1) with pulse durations of approximately twenty to thirty seconds separated by cooling intervals of similar duration. Six to ten pulse cycles are expected to be sufficient to achieve a stable dome geometry at this scale. Between pulses, partial drying is observed through surface temperature monitoring, and reinforcement nodes are repositioned as required.

18.3 Observation Objectives

The prototype experiment is designed to observe and measure several key phenomena: the spatial distribution of cellulose fiber alignment during inflation, the formation and spacing of reinforcement ribs along cable paths, the deformation and dissolution of honeycomb cells under repeated steam exposure, the redistribution of honeycomb fibers onto the inner shell surface, and the stabilization of dome curvature during the final drying phase. After the structure has fully dried, measurements of shell thickness distribution, rib cross-sectional area, final dome height and curvature, and flexural stiffness under point loading can be obtained.

Although such a prototype does not produce a structurally useful building element, it would provide the empirical foundation necessary to calibrate the diffusion coefficient D_h, the drying rate μ, the dissolution rate λ, and the magnetic force coupling constant κ_m introduced in the mathematical model, enabling quantitative predictions to be made for larger-scale implementations.

19 Illustrative Figures

The construction method described in this paper is clarified by a sequence of conceptual diagrams illustrating the principal stages of the process. The following

subsections describe the content of five figures that constitute a schematic construction sequence; detailed technical drawings would be produced in conjunction with experimental prototype fabrication.

19.1 Figure 1: Initial Construction Setup

The first figure depicts the configuration before inflation begins. The foundation ring anchors the perimeter. The flexible membrane substrate lies flat across the ring, and the cellulose slurry layer is distributed uniformly across its upper surface. The reinforcement cable network $\Gamma = (V, E)$ rests above the slurry, with magnetic nodes marked at selected vertices. The paper honeycomb scaffold sits above the cable layer. Annotations indicate the steam injection port beneath the membrane center and the external magnetic field source positioned at the perimeter.

19.2 Figure 2: Steam Inflation Phase

The second figure shows the membrane rising under steam pressure. Steam enters beneath the membrane through the central injection port and the pressure differential drives the membrane upward into a developing dome curvature. Reinforcement cables are shown stretched across the evolving surface, with dashed arrows indicating the direction of magnetic node drift under the applied field. The honeycomb scaffold is shown beginning to deform as the shell expands and the cell geometry accommodates the transition from planar to curved geometry.

19.3 Figure 3: Rib Formation and Geodesic Alignment

The third figure illustrates the development of rib structures. In cross-section, the thickness field h is shown elevated along cable paths, defining the rib set $\mathcal{R}(t)$ as the superlevel region above threshold h_c. A plan view of the dome surface shows the cable network tending toward geodesic paths on the inflated shell, with the interrib surface thinner than the rib regions. The curvature field H is indicated schematically to show the uniformity of the interrib surface contrasted with the curvature transitions at rib margins.

19.4 Figure 4: Honeycomb Dissolution and Inner Layer Formation

The fourth figure shows a detail cross-section of the shell wall during the dissolution phase. The outer cellulose shell formed from the original slurry is intact at the exterior. The honeycomb scaffold, shown in intermediate stages of dissolution, releases fibers that migrate inward through the wet slurry. The inner surface accumulates a secondary fiber layer whose spatial structure reflects the hexagonal geometry of the original honeycomb cells, shown as faint traces in the deposited layer. The total shell thickness $h = h_o + h_i$ is labeled.

19.5 Figure 5: Completed Dome Structure and Envelope Assembly

The final figure shows the completed dome after drying, with the layered envelope assembly of Section 12 included. From exterior to interior the layers are labeled: structural cellulose shell with embedded rib network; inner cellulose reinforcement layer derived from dissolved honeycomb; insulation layer; paper fiber intermediate layer; gypsum interior finish. A cutaway perspective view shows the rib geometry on the outer shell surface and the smooth finished interior surface. A detail inset shows the layer thickness relationships with approximate dimensions corresponding to the prototype parameter values of Table 1.

20 Comparison with Conventional Dome Systems

Table 2 summarizes the principal distinguishing properties of the steam-formed cellulose dome relative to three conventional dome construction systems discussed in Section 9.

The table makes visible the distinctive combination of properties that the steam-formed dome occupies: the only system in the comparison that combines no formwork requirement, no post-construction pressurization, geodesic rib alignment, biodegradability, and high repairability simultaneously. No existing system combines all these properties, which suggests that the steam-formed dome occupies a genuinely unoccupied position in the design space rather than merely recombining existing approaches.

Table 2: Comparison of dome construction systems across key design dimensions.

Property	Concrete thin shell	Geodesic dome	Pneumatic dome	Steam-formed cellulose dome
Formwork required	Extensive	Prefabricated joints	None (air-supported)	None
Geometry source	Mold/formwork	Polyhedral subdivision	Pressure equilibrium	Morphogenetic emergence
Structural medium	Reinforced concrete	Steel or aluminium struts	Tensioned membrane	Ribbed cellulose composite
Pressurization after construction	None	None	Continuous	None
Rib geometry	Designer-specified	Predetermined by subdivision	Absent	Field-guided, geodesic-tending
Primary material	Cement, aggregate, rebar	Steel, aluminium	Synthetic polymer	Plant fiber, water
Biodegradable	No	No	Partially	Yes
Repairability	Difficult	Moderate (strut replacement)	Limited	High (layer separation)
Scalability	High	High	Moderate	Under investigation
Embodied energy	High	High	Moderate	Low (estimated)

21 Morphogenetic Architecture

The steam-formed cellulose dome belongs to a broader class of architectural systems in which form emerges from material processes rather than being imposed through rigid templates. In such systems the distinction between design and fabrication becomes porous: the designer specifies not a geometry but a set of initial conditions, material parameters, and field configurations, and the construction process completes the design by evolving those conditions toward a stable structural state.

This morphogenetic perspective aligns architecture with biological construction processes observed in plants, fungi, and social insects. In each of these cases, structure emerges through the interaction of internal forces and material constraints rather than through explicit geometric planning. The plant stem does not have a blueprint for its cross-sectional geometry; it has a turgor pressure, a cellulose wall, and a set of differential growth rates that together produce a tube with the appropriate mechanical properties for its loading environment. The steam-formed dome operates by the same logic, substituting steam for turgor and cable guidance

for differential growth.

The blurring of construction and growth that results is not merely metaphorical. It has direct practical consequences. Because the dome's geometry is produced by a physical optimization process rather than imposed by a mold, it tends toward efficient configurations even when initial conditions are imprecise. Small errors in slurry deposition thickness, cable placement, or steam pulse timing are smoothed out by the energetic tendency of the system to minimize surface area and bending energy. The dome self-corrects within limits set by the energy functional, making it more robust to fabrication imprecision than a prefabricated system in which every dimension must be controlled independently.

At the same time, the morphogenetic character of the method creates new demands on the designer. Because geometry is not fully specified in advance, the designer must develop intuitions about how material parameters and field configurations interact to produce qualitatively different outcomes. This requires a shift from the geometric reasoning characteristic of conventional architectural design toward the dynamical reasoning characteristic of materials science and biological morphogenesis. The steam-formed dome therefore represents not merely a new building technique but a shift in architectural methodology: from fabrication based on imposed geometry to fabrication based on guided material evolution, and from design as specification to design as cultivation.

22 Discussion

The proposal developed in this paper raises several questions that require investigation before practical implementation becomes feasible.

The structural performance of steam-formed cellulose shells depends critically on the density and alignment of fibers achieved during the inflation-drying cycle. Current understanding of cellulose slurry rheology under steam conditions is insufficient to predict these properties analytically, and experimental characterization of the relevant phase transitions is needed. The dissolved honeycomb contribution to inner layer thickness is similarly difficult to quantify without direct measurement.

The magnetic guidance system described here is specified at the level of principle rather than engineering detail. The force achievable by modest magnetic elements on cable nodes of realistic mass depends on the field strength and gradient achievable with practical external magnets, which will limit the precision with which rib

trajectories can be steered. Robotic field automation, in which electromagnets are repositioned programmatically between steam pulses, offers a path toward more precise control.

Durability and moisture resistance are recurrent concerns for cellulose-based architecture. Treatments including mineral hardening, biocomposite additives, and surface waterproofing have been studied in the paper composite literature and would need to be integrated into the fabrication protocol. The possibility of fiber composite additives, for example mixing short glass or basalt fibers into the slurry to increase tensile strength, merits investigation.

Future research directions include small-scale experimental prototyping to characterize the fiber alignment, shell thickness distribution, and structural stiffness achieved by the method; numerical simulation of the coupled shell evolution equations to explore the parameter space of rib topologies achievable through magnetic steering; and investigation of composite additive formulations that extend the structural and environmental performance of the finished dome.

23   Conclusion

Steam-formed cellulose domes represent a hybrid of pneumatic architecture, fiber composites, and field-guided fabrication. The method proposes that architectural shells can be grown rather than assembled, with geometry emerging from coupled material processes under pulsed pressure, reinforcement guidance, and magnetic steering.

The mathematical model developed here provides a compact formal statement of this idea: dome form and rib topology co-emerge as gradient flows from an energy landscape in which surface tension, curvature regularization, cable tension, magnetic potential, and material transport interact. The honeycomb scaffold contributes a secondary reinforcement layer through steam-induced dissolution, and the cable network tends toward geodesic alignment on the dome surface as energy is minimized during inflation.

The structural logic of the steam-formed dome, in which form is stabilized through iterated regulation rather than imposed by a mold, suggests a broader architectural category that might be called custodial construction. Such structures are not produced by a single decisive act of fabrication but through sequences of interventions that guide an evolving material boundary toward a stable configuration. This

distinction may have implications beyond the specific method proposed here, pointing toward a class of fabrication techniques in which maintenance-like operations and construction operations are not separated in time but are aspects of a unified process.

The dome stands because its boundary was taught how to hold.