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Continuum optimization of 3D printed self-supported shell:
hybrid strategy for crafting ribbed system

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Abstract

Shell structures, commonly used due to their material efficiency, are susceptible to deformation and failure considering the curing time of materials like earthen or cement-based despite their strength. Additionally, they play a crucial role in construction, offering visually striking forms, design flexibility, and efficient load resistance. Masonry shells, represented in arches, domes, and vaults, leverage the strength of materials like Adobe in compression. Yet Shell construction has some challenges while using additive manufacturing such as; the increased material stress, posing potential issues like tensile stress, bending moments compared to standard vertical walls, and the need for supports/formworks at the cantilever spots. The paper aims to identify a strategy of geometries and self-supporting systems capable of sustaining compression forces under gravity loading without formwork with earthen-based material using 3d printing (3DP). To address this limitation, the paper presents a streamlined approach following a strategy that defines the optimized rib position and size to reinforce shells with dynamic behavior that changes according to stress simulations of self-supporting structure, this resulted, an enhanced resilience to external loads and lightweight structure. Several factors affect the optimal reinforcement of shell geometry, such as external loads, surface boundaries, and shape. The method followed used "Ameba" and "millipede" topological optimization tools based on BESO: "Bi-directional Evolutionary Structural Optimization", SIMP: "Solid Isotropic Material with Penalization" methods to showcases the optimum self-supporting system based on directional stress within optimum geometry simulation and mass customization. Utilizing Abaqus voxel-based simulation to simulate displacement in the layer 3DP process and (FEA) finite element analysis that integrates into existing computational frameworks, dynamically reshaping the initial design domain after iterative optimization cycle of the rib across diverse shapes, illustrating enhancements in reducing compliance (strain energy) of 3D-printed objects by defining the optimal amplitude and rib cross-section.

Keywords: Structural optimization, Form finding, additive manufacturing, topological optimization, supporting systems, self-supporting structure, Rib topology.

1. Introduction

1.1.Shell structure optimization in structural engineering is recognized for its exceptional efficiency, offering a balance of lightweight construction and strength. This makes them particularly well suited for additive manufacturing applications, where employing shell structures instead of solid one's results in cost reduction due to less material usage and faster fabrication processes. Shell structures whose shapes are determined by factors other than external loading are frequently strengthened through supplementary methods, typically involving reinforcing critical areas by increasing thickness or incorporating ribs (Fig.1)[1][2].

1.2.Problem formulation Designing shell structures presents considerable challenges, stemming from four primary aspects:

-Determining the optimal quantity of ribs or stiffeners required.

-Selecting appropriate locations for rib placement along shell stresses.

-Identifying an efficient rib cross-sectional and amplitude configuration for constructing shell structures using 3D printing (3DP) technology with earth-based materials.

-Finding optimal rib network by leveraging optimum topological optimization methods.

The exploration of these previous aspects serves the main purposes: minimizing strain energy and maximizing structural stiffness. To accomplish these objectives, we present a computational framework for designing and refining rib topologies throughout the formulation of the shell structure. Our strategy focuses on strategically placing ribs along primary stress paths, enhancing the stiffness of the shell, and optimizing its structural integrity. This tailored approach is geared toward maximizing mechanical effectiveness, particularly suited for the intricacies of 3DP in shell construction [2][4].

1.3.Shell principal stresses

In the construction of principal stress lines, we delved into the concept of principal stress directions. Initially, any structural continuum can be dissected into tiny cubical elements to depict stress states at each point. In a two-dimensional structural continuum, stress states are uniquely described by two normal stress components and one shear stress component. Stress states remain constant upon rotation of these elements, yet their components align with the new orientation. This phenomenon, known as stress transformation, facilitates the identification of planes with distinct stress characteristics. Specifically, principal stress directions denote orientations where shear stress is absent and normal stresses are maximized [2][5][6].

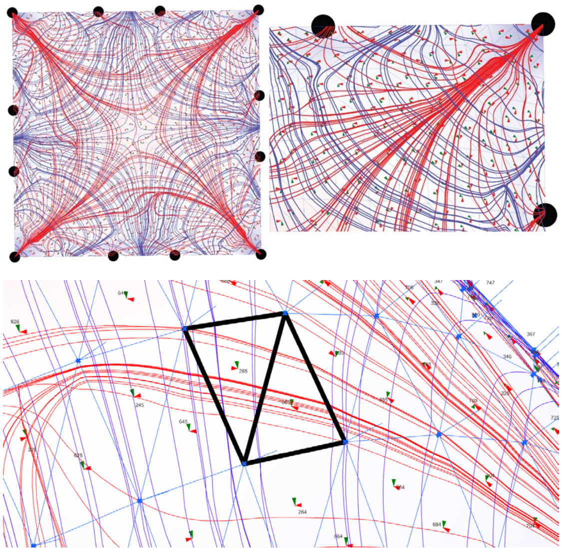


Figure 1: Principal stresses represent the minimum and maximum normal in-plane stresses experienced at a specific point within a shell structure, as illustrated by the position vectors, these stress lines delineate optimal orientations for reinforcing elements within the shell elements.

1.4.Shell required thickness The parameter (t) represents the thickness of the shell, while (R) represents the local radius of curvature. The ratio t/R is used to determine whether a shell is considered "thin," with a t/R value of 0.01. shell stress resultants for shells with t/R less than about 5 percent of the local radius. Additionally, the thickness ratio t/R is used to determine the stability of arches and domes[3].

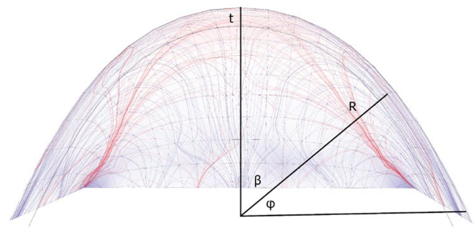


Figure 2: (φ,β) (30°, 60°) denotes cut-off angles.

By determining a sufficient number of principal stress planes across the structural body, we construct the principal stress line field by linking these projections. Structural designers find principal stress lines invaluable as they offer insights into the natural flow of forces as shown in (Fig.1)(Fig.3) exerted by applied loads. This visualization highlights areas of material continuity crucial for design coherence within the specified domain [4][5][6].

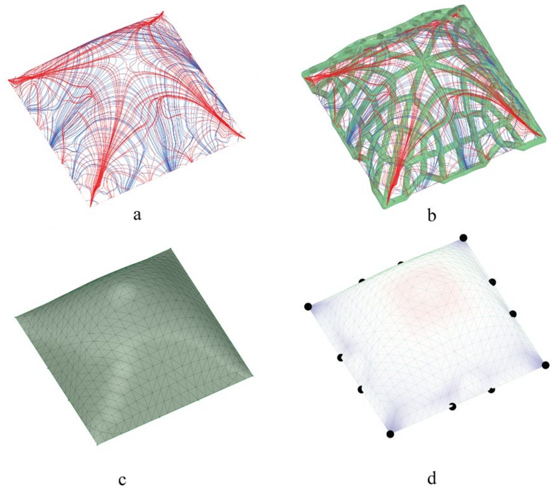


Figure 3: The initial stage of articulating shell structure through identifying initial (a) stress lines, (d) boundary conditions and principal stresses, (c) Meshing, and (b) ribs.

1.5. Rib amplitude and overhang angles rib-shell structures amplitude denote the vertical extent or magnitude of the ribs, which are primary load-bearing components. For instance, in the context of shell roofs, rib amplitude influences the overall structural performance, including load-carrying capacity and resistance to deformations [7].

a b

Figure 4 : (b)An example of a printable stoneware clay-based ribbed shell surface,(a)overhang angle simulation (40.50°).

The overhang angle relates to the inclination or tilt of the overhanging portion of a shell structure relative to the horizontal plane. This parameter is significant in the construction 3d printing architecture context, as it affects the structural stability properties and functionality of the shell assembly. This study identifies side parameters (a_n,φ) as part of the shell optimization process and the influence of overhang angles on the stability of the fabrication initial phase[7].

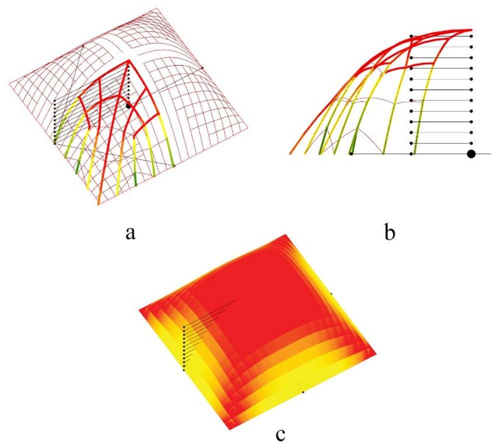


Figure 5: In the initial phase of the defined problem, we simulate the overhang angle for a quarter of rib shell curves.

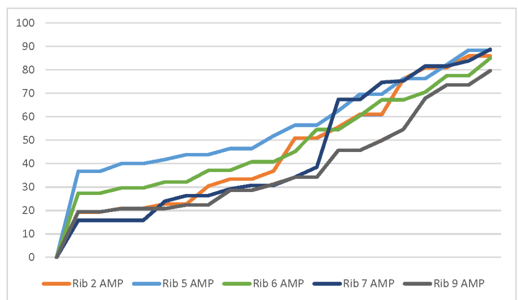


Figure 6: 3D Printing ribs with amplitudes between (50 to 80) degrees, as illustrated in Figure 5,

presents obstacles in 3D printing, this matter will be a focal point in our optimization and form-finding methodology.

1.6. Global and Local Inertial Properties: The Local inertial properties influence mass distribution and resistance to displacement at a micro-level within the structure, particularly examining how individual components like ribs contribute to overall inertia. Conversely, the global perspective encompasses the collective behavior of all elements, reflecting the structure's entirety regarding mass distribution and resistance to movement. Both perspectives are crucial for comprehending the structural dynamics of shell structures and addressing challenges like buckling in the 3D printing process.

Subsequently, we subject it to an external load and conduct Finite Element Analysis (FEA) to analyze its behavior. Based on the FEA outcomes, we derive the principal stress field across the surface, indicating favorable material continuity and encoding the optimal topology.

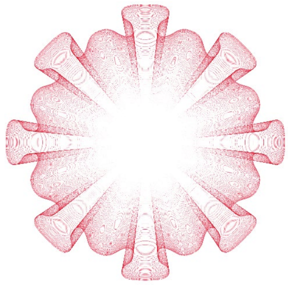


Figure 7: A fully ribbed shell surface, demonstrating the emulation of global inertia using a Grasshopper algorithm.

Our objective starting from the initial phase, we establish a global parametrization based on the stress field and align a mesh with these directions. From this mesh, we derive the initial path for the rib network. Moving into the second phase of the optimization methodology, we strategically place ribs along two orthogonal directions, guided by the maximum principal stresses on the shell surface. Following this, we conduct FEA analysis and utilize topological optimization methods, emphasizing constraints that minimize compliance while maximizing the shell structure's stiffness within the specified mesh domain. Finally, we select the most optimal rib network in the final phase.

2. Motivation and related works

In the field of architectural geometry, the predominant focus lies on optimizing the geometric attributes of polygonal meshes, particularly quadrilateral meshes used for approximating free-form surfaces. Numerous endeavors are dedicated to ensuring face planarity, including the development of planar quad meshes, cell packing meshes, and polygonal or hexadecimal dominant meshes[1]. some approaches aim to approximate surfaces by uniting patches known as panels. However, only a handful of studies consider structural aspects for the layout of PQ meshes approximating given freeform surfaces, In the field of architecture engineering, the exploration of rib-stiffened shell structures has attracted considerable attention from expert researchers, much of this inquiry has revolved around dissecting the behavior of specific rib-shell configurations, particularly emphasizing how ribs fortify surfaces against diverse external loads. While numerous studies have scrutinized the optimization of rib dimensions, forms, or placements to bolster overall structural performance, only a select few have delved into the intricacies of rib design within a given shell[2]. Pioneering research has introduced automated approaches for rib placement. One such method involves optimizing shell thickness initially and then identifying rib locations where thickness exceeds a predefined threshold [9]. another innovative technique termed the adaptive growth approach, commences with the initiation of stiffeners from seed points, allowing them to expand and branch towards regions where they maximize global mechanical effectiveness [10]. this process, driven by the structural sensitivity of the existing design, harnesses optimal rib shapes and positions to reinforce structural stiffness through topology optimization methodologies. Furthermore, the application of particle swarm algorithms has been proposed to fine-tune rib placement[11]. nevertheless, the majority of these investigations have predominantly focused on relatively simplistic or arbitrary surfaces. Addressing the challenge of designing rib-shell structures for complex, arbitrary 3D freeform surfaces remains an ongoing endeavor[], Notably, a framework has been proposed for generating grid-shell structures with exceptional static performances, leveraging Voronoi diagrams in the process. This innovative approach underscores the ongoing quest among researchers to push the boundaries of rib-shell structure design and optimization, particularly in the context of intricate and irregular geometries, The form-finding process comprises several optimization cycles, with each cycle composed of numerous iteration steps (Iterative design updates are performed to adjust the parameters of the ribs and the overall shell geometry based on the optimization objectives and constraints) [8].

3. Shell form finding for 3d printing

Shell form finding for 3D printing involves the intricate process of creating optimal geometries that can be efficiently manufactured using additive manufacturing techniques. This methodology emphasizes the exploration and refinement of structural shapes that not only fulfill functional requirements but also leverage the capabilities of 3D printing technology. considerations such as geometric complexity, support structures, and printing constraints are carefully addressed to ensure successful fabrication. Ultimately, the goal of shell form finding for 3D printing is to produce innovative and optimized designs that push the boundaries of shell construction (3DP) possibilities .

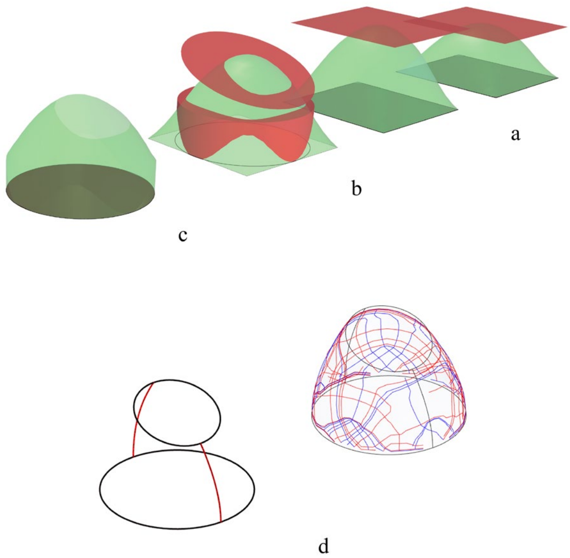


Figure 8: This figure illustrates the process of form-finding for a shell structure intended for 3D printing by minimizing maximum stresses through the reformulation of its geometry

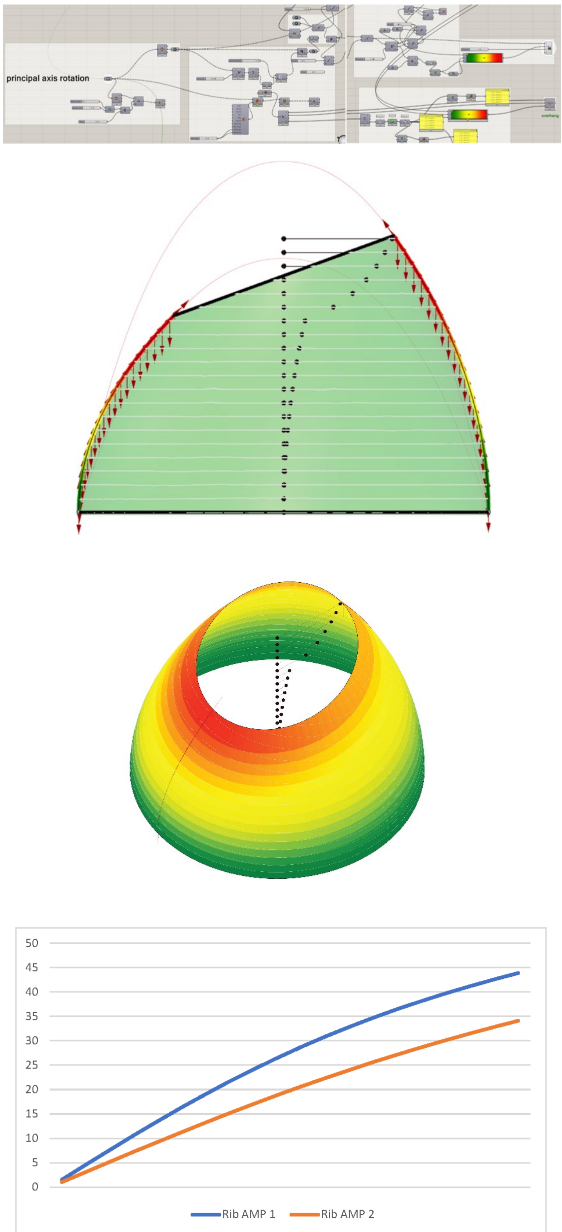


Figure 9: Maximum overhang angle (45∘)

In the process of initializing rib topology, we consider side parameters such as rib Size, position, and amplitude.

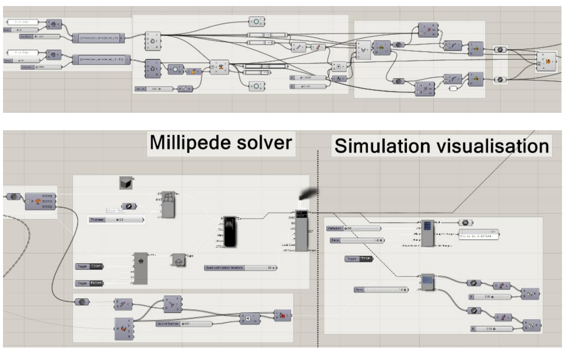


Figure 10: Millepede simulation Algorithmic code.

4. Material and method

In this section, the composition and preparation of the earth-based composite utilized in the study are elucidated. The composite is formulated by blending various constituents, including 70% earthenware fine powder, 15% sisal fiber, 15% aggregates, and natural lime. This composition is meticulously chosen to facilitate the 3DP process for construction applications. Notably, the earth-based composite's suitability for construction is substantiated through compressive strength testing, revealing its capacity to withstand a load of 2570 newtons with a displacement of 3.29 millimeters. These empirical results serve as pivotal inputs for defining the material properties within the AMEBA topological optimization framework. By accurately characterizing the mechanical behavior of the composite, informed decisions can be made regarding its utilization and optimization in structural design, thereby enhancing the efficiency and efficacy of construction methodologies.

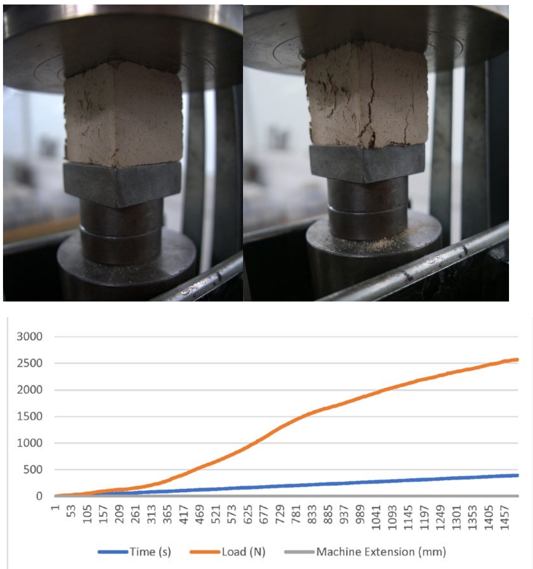
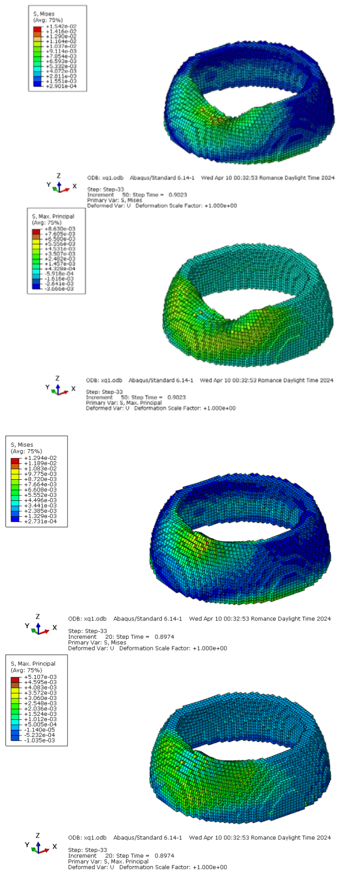


Figure 11: compressive strength test 1.028 N/mm2

(a)



(b)

Figure 12:

(a) Demonstrating a 1:2 ratio prototype test through 3D printing to analyze material behavior and establish output parameters for optimization simulations, (b) Conducting displacement simulations utilizing the Abaqus voxel-based method on the developed geometry with concrete parameters.

5. Optimization Methodology

Typically, the primary optimization objective for reinforcing shell structures is to minimize the weight and strain energy of the additional material while ensuring that the maximum stress within the structure remains within acceptable bounds to maximize the stiffness of the structure this problem has been well-studied by focusing on devising a computational framework for designing and refining rib networks within shell structures. Our method:is strategically to position ribs along the principal stress lines to enhance the shell's stiffness. Additionally, we employ topological optimization simulation methods based on BESO "Bi-directional Evolutionary Structural Optimization" and SIMP "Solid Isotropic Material with Penalization" to achieve an optimal mass distribution, considering specific constraints related to rib cross-section, amplitude, and boundary conditions. The approach followed through drawing inspiration from principal stress lines to inform the design of the rib-shell structure. The objective is to strategically position ribs on the surface, aligning them with the principal stress lines for optimal structural performance through an adaptive optimization method.

BESO workflow: - Define shell mesh domain volume where the optimized structure will be located..

- Loads and Constraints: Specify the loads (such as gravity forces) and constraints (such as fixed supports) that will affect the performance of the structure. These parameters define the boundary conditions for the optimization process.

-Generate Finite Element Mesh: Ameba automatically generates a finite element mesh based on the defined design space, loads, and constraints. This mesh discretizes the design space into smaller elements for analysis.

-Defining material properties and optimization convergence parameters.

-Perform Optimization: Ameba iteratively adjusts the distribution of material within the design space to minimize compliance and maximize stiffness, while satisfying the specified loads and constraints. This is typically achieved by removing material from low-stress areas and redistributing it to high-stress areas.

Computational framework Here, we reveal a computational framework for generating and optimizing ribs on uniform shell surfaces, utilizing 3D printing parameters tailored to construction printing processes.

In our approach, we draw inspiration from principal stress lines to inform the design of our rib-shell structure. Our objective is to strategically position ribs on the surface, aligning them with the principal stress lines for optimal structural performance through an adaptive optimization method.

The development of functions tailored for the additive manufacturing process of a shell structure, including reinforcement elements (ribs), involves adapting the current optimization framework to meet the precise needs of the fabrication process and the integration of reinforcement elements. The goal is to optimize the total volume of the shell structure while incorporating reinforcement ribs to support the structure and choosing the optimum amplitude of the ribs based on the global inertia of the shell geometry.

Total Volume Optimization:

The existing optimization problem for compliance minimization can be adapted to optimize the total volume of the shell structure. This involves modifying the objective function and constraints to focus on minimizing the total material volume while ensuring structural integrity.

Incorporating Reinforcement Ribs: To incorporate reinforcement ribs into the shell structure, the design variables can be extended to include parameters related to the presence, size, and distribution of the ribs within the shell geometry. This may involve introducing additional design variables to represent the ribs' characteristics.

$$min\ c(x) = \frac{1}{2} * (U^T\ kU).Vr \qquad (1)$$

$$Vr = \sum_{i=1}^{n} (vii)*(\text{vi}) \qquad (2)$$

Where $c(x)$ represents the total compliance of the structure in the context of compliance minimization, (U) is the global displacement vector, (K) is the global stiffness matrix, the superscript (T) denotes the transpose operation,(Vr): represents the volume of the reinforcing ribs,(vii) : represents the number of ribs at each node, (vi): represents the volume of each rib, (n) : is the total number of nodes in the shell structure.

Results Example 1

Initial ribbed shell volume (1.1887e+7)

Optimized Rib shell Volume (0.5) ratio

iterative 21

Rib size (40,20)cm

Vr : 179.69cm3

Rib amplitude range (40 to 45) degree

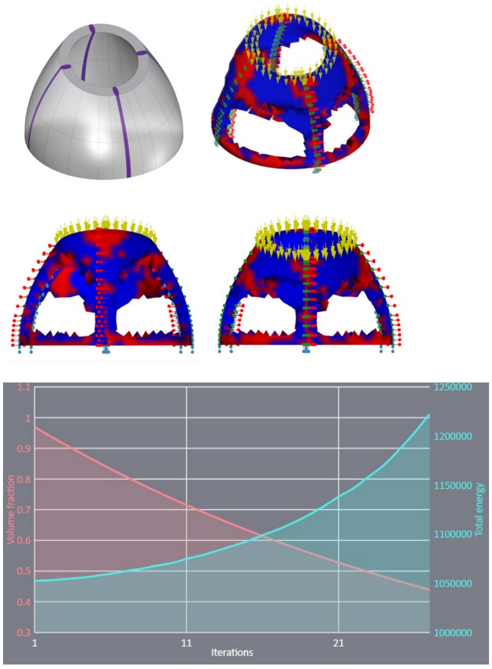


Figure 13: An optimization instance of a shell structure reveals elevated strain energy concentrated within the volume of the ribs Vr.

Result Example 2 :

Initial shell volume (1.1922e+7)

Optimized Rib shell Volume (0.65) ratio

(1.3665e+7)

iterative 21

Rib Size (40,20)cm

Vr : 179.69cm3

Rib amplitude range (40 to 45) degree

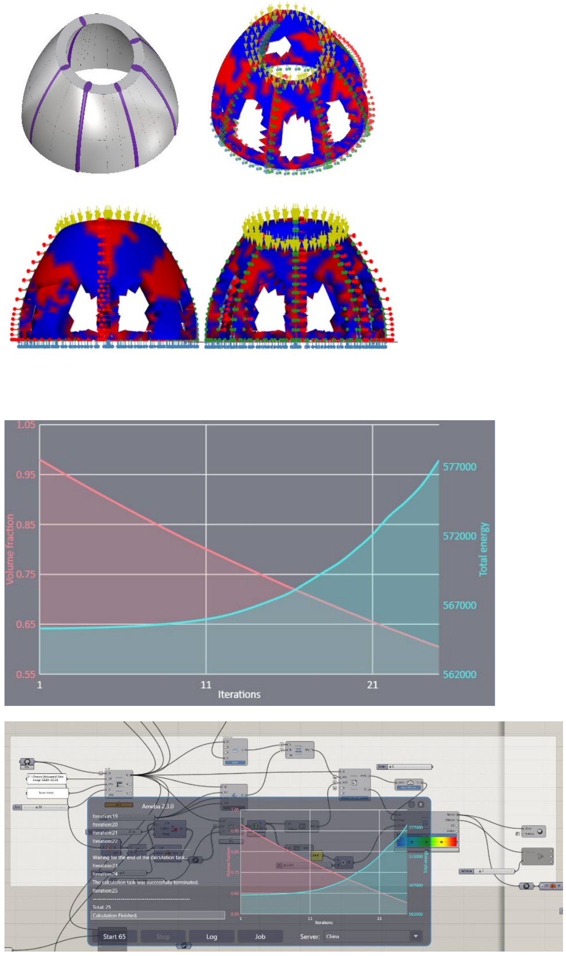


Figure 14: An example of shell optimization demonstrating a reduction in strain energy surrounding the rib volume.

6. Results and discussion

The optimization results obtained through the BESO method demonstrate significant alterations in the mass distribution ratio between solid and void regions, as depicted in the figures. Notably, the inclusion of ellipsoid-shaped cross-section ribs or stiffeners within the shell structure, within the defined mesh domain, induces a discernible decrease in the size of void regions. This observation is consistent across simulations conducted with AMEBA, wherein a reduction in strain energy or compliance, particularly evident in Example 2, is observed compared to the SIMP method.

Furthermore, in contrast to void regions, the utilization of Millipede simulations, focusing on stiffness factors, reveals a notable increase in thin surface area representation. This result underscores the importance of considering not only void regions but also the distribution of surface areas when optimizing shell structures., The initial thickness of the shell, is determined based on the radius of curvature (R) and the span (L0, L1) to the center of the shell, employing a percentage ratio of thickness to radius (t/R). This method of thickness determination offers adaptability across various shell envelope geometries.

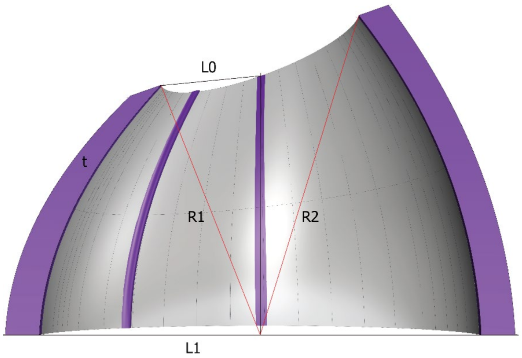


Figure 15: Preliminary shell envelope parameters (L0, L1, R1 , R2).

The optimization process involves defining material properties such as **Young's modulus(2.18), Poisson's ratio(0.215), and material density(5.47)kg/m3**, along with specifying boundary conditions. Boundary conditions encompass the curvature of the shell boundary curve and support points' constraints on the ribs, as well as the gravity load. These inputs collectively influence the resulting mass distribution.

The final optimization parameters: **Volume target (30%), Evolutionary ratio(2%),Filter radius (1), Maximum iterations (21 to 25)**.

The final quantitative results of the optimization objective aim to minimize the function **min c(x)**, where reducing **strain energy (Es)** is achieved by increasing the number of **(Vr)** ribs. This formulation emphasizes the optimization goal of enhancing structural performance by redistributing material mass within the shell structure, thereby improving its mechanical properties and efficiency.

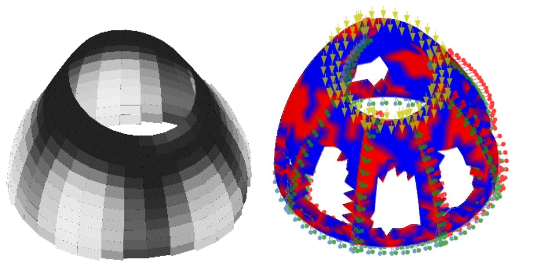


Figure 16: Optimization results using (Using SIMP and BESO) algorithms.

7. Optimization strategy for additive manufacturing shell structures

7.1. shell structure classifications

7.1.1. Flat slabs

The possibility of employing additive manufacturing AM to construct flat slabs using the discretization method presents intriguing opportunities for innovation in building technology. By breaking down a flat slab into discrete elements that can be individually printed, this approach could offer enhanced control over material distribution, allowing for optimization of structural integrity and material efficiency. This method could revolutionize traditional construction practices by enabling the customization of slabs to meet specific load-bearing requirements while potentially reducing material waste and construction time. However, the success of this endeavor hinges on advances in AM technology, particularly in terms of print resolution, speed, and the development of construction materials (concrete and earth) that meet rigorous structural standards. If these technological and material challenges can be overcome, using AM for flat slab construction could significantly impact architectural design and construction methodologies.

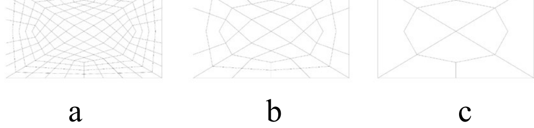


Figure 17: Initial discretization approach for a flat slab using the SPIDER simulation tool, which is a structural form-finding method capable of simulating various models of hanging chains, (a) maximum iteration, (b) average iteration, (c) minimum iteration.

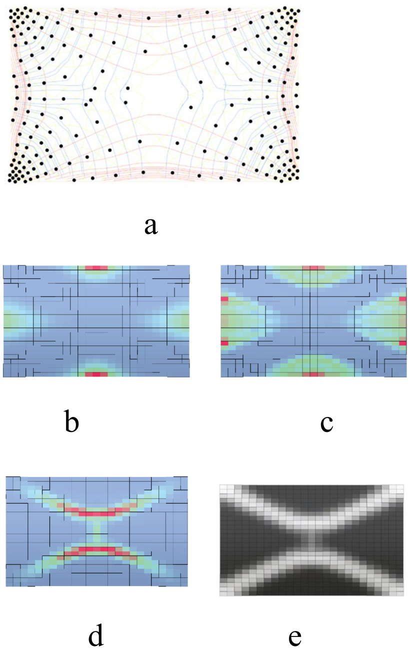


Figure 18: The Millipede optimization tool is employed to simulate stress lines (a) within the boundaries of this flat slab. Additionally, it aids in identifying key structural parameters including (c) maximum von Mises stress, (b) displacement, (d) bending moment, and (e) stiffness factor.

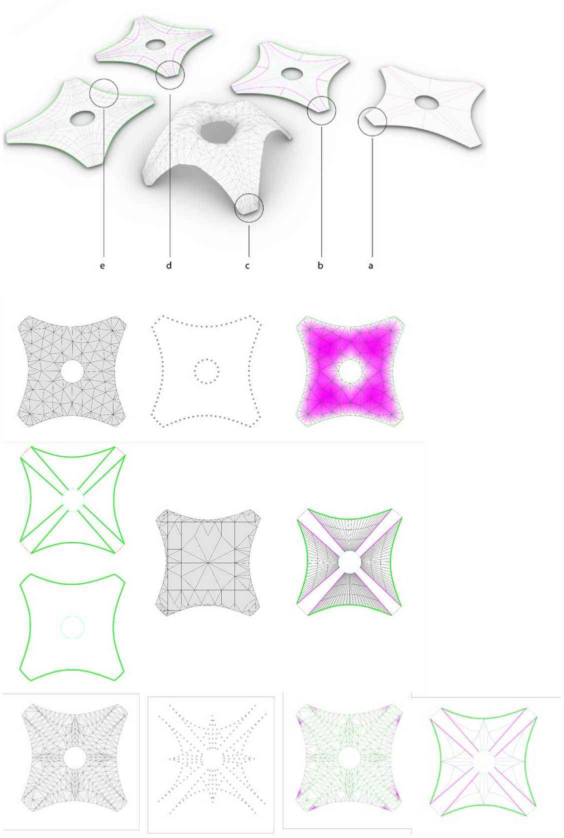


Figure 19: The process involves identifying the mesh network by defining the boundaries and employing a procedural method for surface modeling to achieve integrated mesh topologies using Karamba 3d and Kangaroo 2 physical and structural simulation tools.

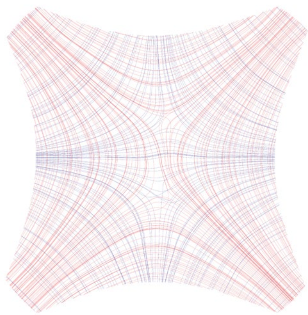


Figure 20: Simulating stress lines is a crucial component of the computational workflow process.

7.1.2. Domes

The designing and optimizing domes for AM with viscous materials such as earth-based composites offer a promising avenue for sustainable and efficient construction. These materials provide cost-effective solutions with a low environmental impact due to their local availability and inherent sustainability. The structural integrity of domes, enhanced by their shape, allows for the effective distribution of loads, thus utilizing the mechanical strengths of earth-based composites. However, challenges related to the material's viscosity require advanced printing techniques to ensure stability and durability during the construction process. To address these challenges, we are actively developing and refining various strategies for AM these structures, employing computational tools such as finite element analysis to optimize design and performance. This ongoing development in printing techniques signifies a step forward in scaling and adapting this technology for diverse construction needs, potentially revolutionizing how we approach building complex structures with natural materials.

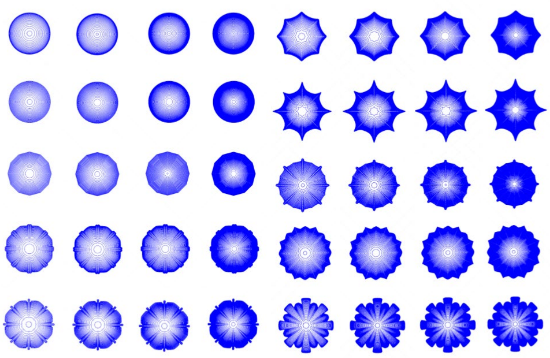
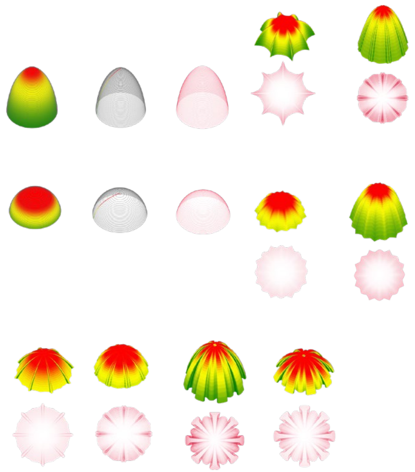


Figure 21: The initial layering process for designing domes and the continuous additive manufacturing process involves varying the surface mass and enhancing global inertia by incorporating a corrugated surface design, which includes the addition of stiffeners such as ribs and kinks.



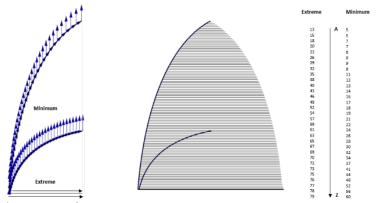


Figure 22: An algorithm has been developed using Grasshopper to simulate the overhang angle of different dome structures, enabling the selection of the optimum amplitude for the additive manufacturing process.

7.1.3. Barrel vault

The barrel vaults for the AM process introduce a complex set of challenges and considerations, primarily due to the intricate curvatures and structural demands of these architectural forms. some key conclusions drawn from the exploration of this complexity :

Geometric Complexity: Barrel vaults feature continuous curved surfaces that can be challenging to extract accurately in an AM context. Ensuring geometric precision is crucial to maintaining the aesthetic and functional integrity of the structure.

Structural Integrity and Load Distribution: The unique shape of barrel vaults offers excellent load distribution properties, but optimizing these in a 3D printed structure requires precise calculations and adaptations in the design to accommodate the material properties and printing capabilities.

Printing Techniques and Parameters: The complexity of printing curved structures like barrel vaults necessitates advanced 3D printing techniques. Parameters such as layer height, printing speed, and support structures must be meticulously planned and adjusted to handle curves and overhangs without compromising the structure.

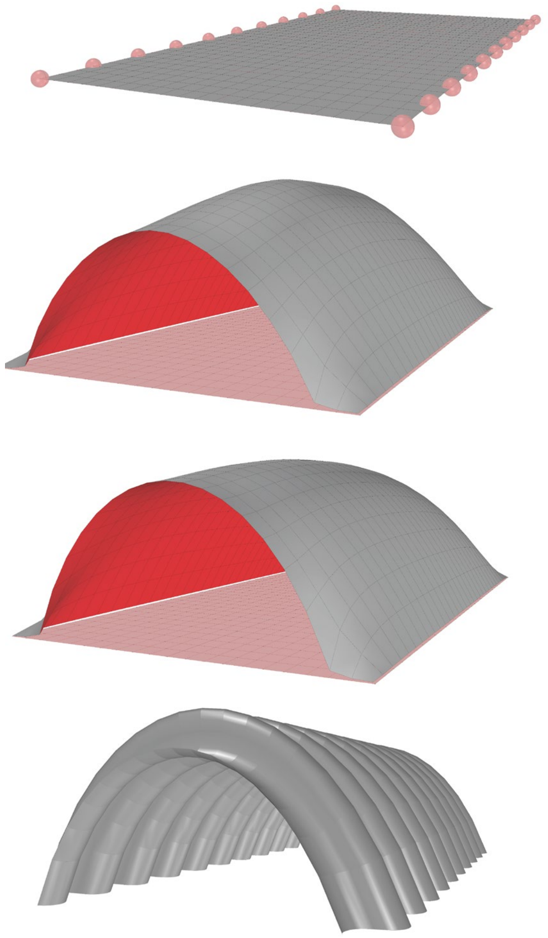


Figure 23: 3d modeling a barrel vault using Kangaroo 2 for the 3D printing process is conducted without the implementation of optimization techniques.

7.1.4. Cross vault

The possibility of using additive AM to construct cross vaults presents an intriguing opportunity for innovation in architectural design and construction. Cross vaults, known for their intersecting arched forms that create a structurally sound and visually appealing ceiling or roof, could greatly benefit from the advancements in AM technology. several points highlighting the potential and challenges of this application:

One of the primary advantages of AM is its ability to handle complex geometries with a high level of precision. Geometrically intricate cross vaults.

Structural Integrity: The structural design of cross vaults using AM must be rigorously analyzed to ensure safety and stability. This involves not only the proper architectural and engineering design but also the adaptation of print paths and strategies to optimize load distribution and minimize weaknesses by developing a series of topologies for stiffeners to support the AM process.

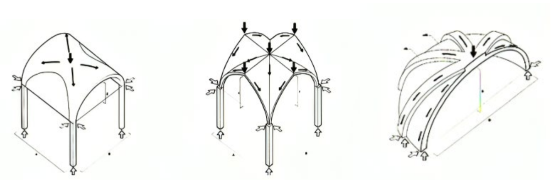


Figure 24:load distribution for three building typologies such as (barrel and cross vault with dome)[12].

7.2. Theoretical to practical translation

The theoretical framework for rib-reinforced shell structures has direct implications for practical scenarios in additive manufacturing A.Some key points that bridge the theoretical aspects of rib-reinforced shell structures with their practical application in additive manufacturing:

Material Efficiency: The theoretical focus on minimizing material usage while maintaining structural integrity is highly relevant to additive manufacturing, where material costs and efficiency are critical factors. The optimized rib-reinforced shell structures can lead to more cost-effective 3D-printed parts.

Design for AM: The method of placing ribs along principal stress lines to enhance structural performance is particularly useful in additive manufacturing, where complex internal structures can be realized without the limitations of traditional manufacturing methods. This allows for the creation of lightweight, high-strength components that are difficult to achieve with other manufacturing processes.

Topology Optimization: The theoretical approach to topology optimization, which includes the simplification and flow optimization of rib networks, can be directly applied to the design of 3D printed parts. This ensures that the final printed structure is not only mechanically complete but also efficiently designed for the AM process, reducing print time and material waste.

FEA Integration: The use of Finite Element Analysis (FEA) in the design process is a common practice in additive manufacturing to predict the mechanical behavior of parts before they are printed. The framework's reliance on FEA to inform rib placement and optimization is a strategy that aligns well with the design workflow in AM.

Printability and Overhangs: In practical AM scenarios, the design must consider the printability of the part, including the management of overhangs and support structures. The optimized rib-reinforced shell structures can be designed to minimize the need for support material, reducing post-processing and improving the overall efficiency of the printing process.

In summary, the theoretical framework for rib-reinforced shell structures provides a strong foundation for the practical application of additive manufacturing. By leveraging the unique capabilities of AM, such as the ability to produce complex internal geometries, the framework can be used to create efficient, high-performance structures that are optimized for both material usage and mechanical performance.

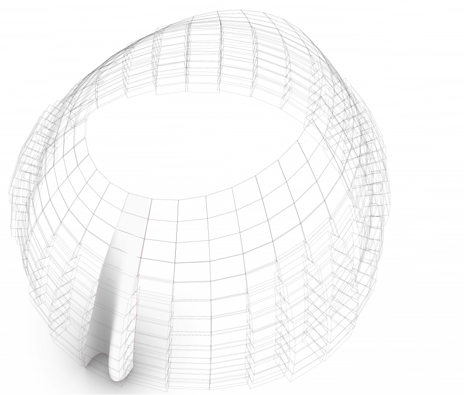


Figure 25: The workflow developed with the Millipede optimization tool provided a simulation of mass distribution in the form of components like

bricks or voxels. This is beneficial for accurately identifying the shape of the infill geometry within the shell structure, ensuring precise mass simulation alignment.

7.3. Remark conclusion

In conclusion, this research identifies hybrid strategy for crafting ribbed systems" introduces a groundbreaking approach to the design and construction of shell structures using AM technology with earth-based materials. The novel hybrid strategy, which integrates topological optimization tools and finite element analysis, enables the creation of self-supported ribbed systems that enhance structural resilience and efficiency.

The research demonstrates a clear translation from theoretical models to practical applications, with a focus on the accuracy and applicability of the optimization techniques to real-world fabrication geometries. The use of earthen-based materials adds an ecological dimension to the work, aligning with the growing interest in sustainable construction methods.

In summary, this research presents a method that is not only innovative in its approach to structural optimization but also holds great promise for the future of architectural design and construction, particularly in the context of construction additive manufacturing.

Building complex structures such as shells using AM earth-based composites poses a significant challenge in ensuring stability, flowability, and buildability during material deposition. The scale of the structure and the extrusion system play crucial roles in achieving optimal material behavior and machine performance is clarified in this paper.

In AM shell construction, higher stresses in the material compared to standard vertical walls can lead to potential issues such as tensile stress and bending moments, posing a risk of structural failure during fabrication. To mitigate this risk, material formulation and printing set-up need meticulous optimization.

This paper's simulations encompass various inputs, including geometric considerations such as boundary conditions, and overhang angle, crucial for accurately optimizing AM structures. Creating dependable toolpaths for shell structures during the AM process remains a challenge.

Future work can focus on addressing this challenge by enhancing computationally this novel computational modeling strategy based on topological optimization methods.

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